A Review of Smart Energy Projects & Smart Energy State-of-the-Art

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Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

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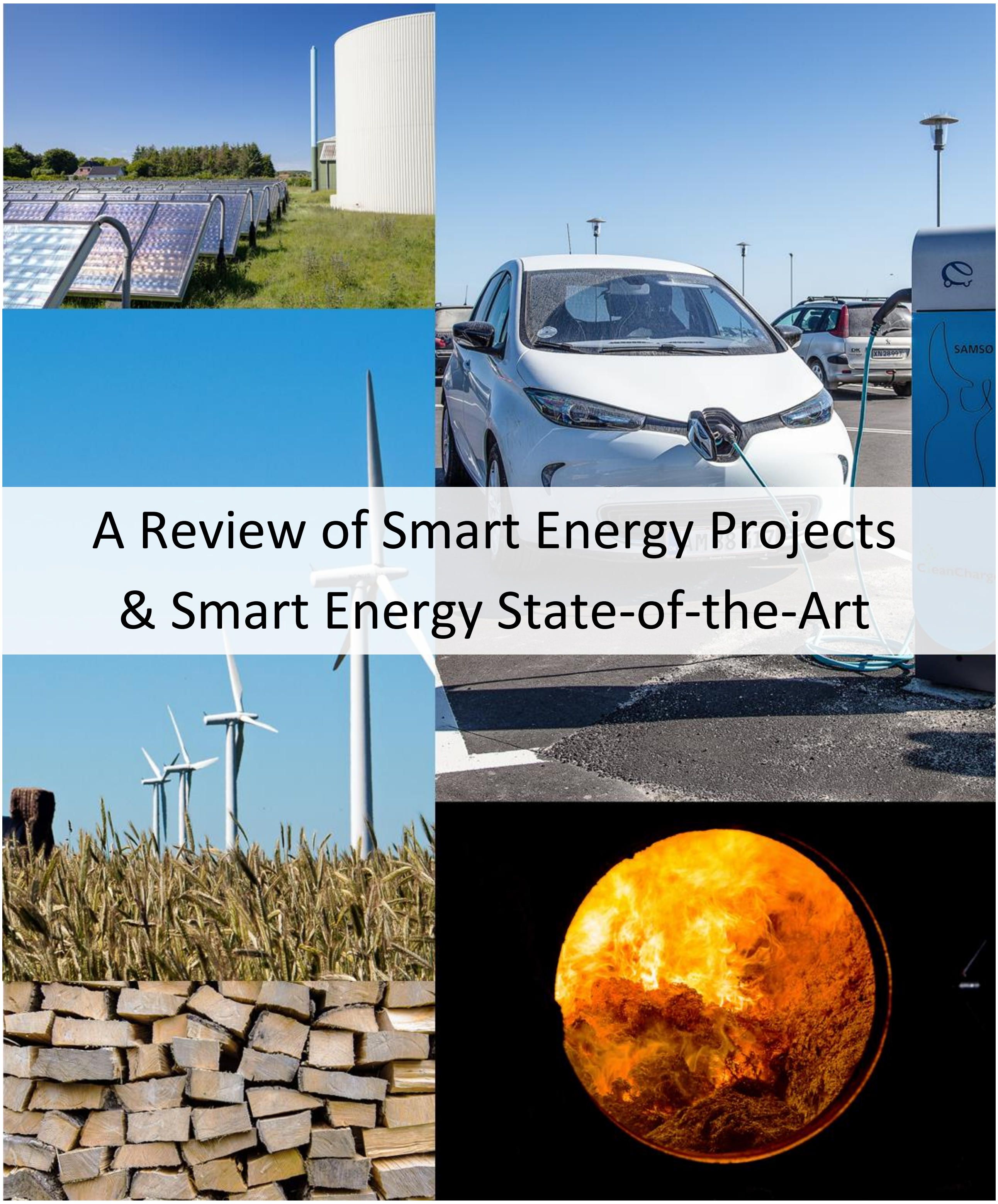

Smart Energy Networks
Research, Development and Demonstration

EUDP
Energiteknologisk udvikling og demonstration

AALBORG UNIVERSITY
DENMARK

A Review of Smart Energy Projects &
Smart Energy State-of-the-Art

December, 2015

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Publisher:

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Vestre Havnepromenade 5
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Denmark

ISBN: 978-87-91404-77-1

Cover page photos: Samsø Energy Academy, Birger Jensen, Erik Paasch Jensen, Franseska Mortensen and Jørgen Bundgaard

This report has been prepared and edited by researchers at Aalborg University. Its findings and conclusions are the responsibility of the editorial team. A database of 225 Danish research projects is made available as part of this report. The database and report can be downloaded from www.vbn.aau.dk.

The report has been commissioned by the Smart Energy Networks partnership to qualify the development of a Danish National Roadmap for Smart Energy RD&D. The work is supported by EUDP – Energy Technology Development and Demonstration Program.

Acknowledgements
The project is partly funded by EUDP through the Smart Energy Networks Partnership. The report forms the basis for an update/extension of the "*Roadmap for Forskning, udvikling og demonstration inden for Smart Grid frem mod 2020*" [1].

The Smart Energy Networks Partnership is Denmark's national public-private partnership for Smart Energy. The network acts as catalyst and initiator of a strengthened strategic agenda for research, development and demonstration (RD&D) that will support energy policy goals as well as attractive and sustainable growth conditions for Danish trades and industries. The network brings together the Danish energy companies, industry and knowledge institutions within electricity, heating, cooling and gas. The network was established in 2014 and the role of the partnership is to enable optimal exploitation of resources through strategic planning for Research, Development and Demonstration of integrated and intelligent energy systems. The network is supported by the Energy Technology Development and Demonstration Programme (EUDP).

http://www.smartenergynetworks.dk/

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Executive summary

The aim of this study was to investigate the research projects in Smart Energy over the past 10 years in Denmark, the Nordic region and the EU in order to find gaps and to inform the Smart Energy Network's recommendations. The study also investigated the Smart Energy state-of-the-art research based on expert knowledge. Smart Energy is a cross-sectoral approach that makes use of synergies between the various energy sectors when identifying suitable and cost-effective renewable energy solutions. The three main energy sectors involved are electricity, thermal and gas. Different sub-sectors form parts of these sectors, for example electric vehicles in the electricity sector, and district heating in the thermal sector [2].

In this study a database of Danish projects was made that labelled each project with their Smart Energy focus and other metadata such as funding body, and type of project. The database is publically available.

In this executive summary the main findings for the four research topics in the study are described. This is followed by more concrete conclusions for the analysis of Smart Energy projects in Denmark, the Nordic region and the EU. Lastly the Smart Energy state-of-the-art research is summarised.

1. Past and current Smart Energy efforts

The main contributors to the Danish energy research has granted almost 8 billion DKK in the last 10 years. This has been supplemented by co-financers, for example industry, to a total of almost 15 billion DKK. Within Smart Energy in the last 10 years (2005-2015) the research projects have increased steadily. In this report it was found that the granted funding in the Smart Energy area has increased significantly from negligible levels in 2005 to a cumulative total of almost 1.5 billion DKK in 2015. The total budget for all the projects is 2.6 billion DKK. The projects included in this analysis (225 in total) represent 95% or more of all the Smart Energy research projects in Denmark during this period (See Figure 1 for a breakdown of the total number of projects and the level of funding from different funding bodies in Smart Energy in the period 2005-2015).

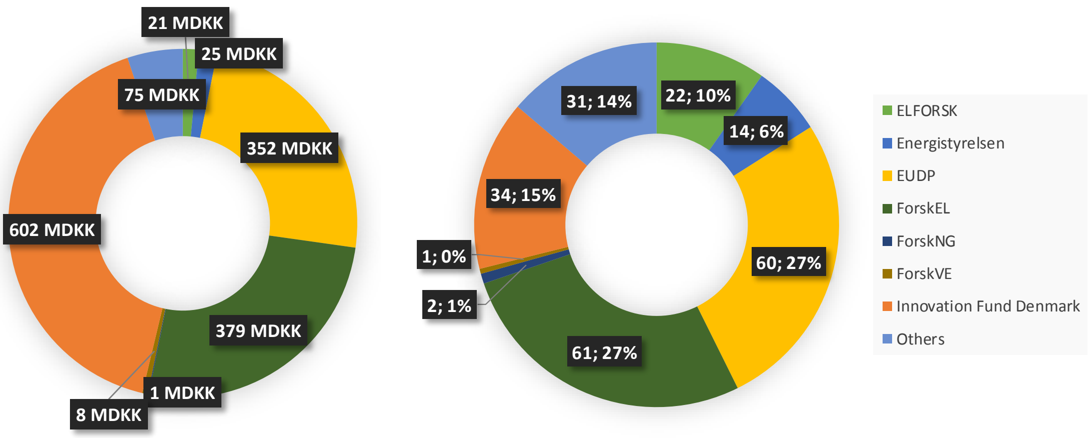

Figure 1: Granted funding, in MDKK, per funding body in the period of analysis (left).
Number of projects funded per funding body in the analysis period, in absolute numbers and in percentage (Right).

In recent years there has been a rather intensive and large activity in all Nordic countries concerning Research, Development and Demonstration (RDD) in the field of smart electricity grid research. In all Nordic countries, national cooperation of actors within networks involved in Smart Grid research and experimentation has been created.

The European Commission has invested 112 MEUR in the theme of smart electricity grids in Europe and this funding grew until 2012 at its peak. Regarding the thermal sector, the research funding has been sporadic and less consistent compared with the Smart Grid projects. In regards to transport fuels in the European context no projects were identified that investigated cross-cutting sector integration between electricity and liquid or gaseous fuels. But some projects investigated integrating smart electric vehicles with the electricity grid.

2. Development tendencies on the Smart Energy funding domain

The granted funding for Smart Energy projects has increased steadily year on year from 2005 to 2011, but in recent years the funding level has stayed constant. The granted budget has been around 200 million DKK pr. year over the last 5 years, where the electricity sector has received the majority and the thermal sector the lowest levels. In Denmark, in the first few years of Smart Energy research, focus was placed on projects that research only one energy sector. The majority of single sector projects focused on the electricity sector and the majority of research areas are in the electricity sector. There is a tendency that other sectors than electricity are more and more in focus and that more projects include two sectors (e.g. electricity and gas) in the most recent years.

Most research projects are not inter-disciplinary but rather focus on two to three research areas. Non-technical issues have a rather low level of funding. In the EU there has been a lot of focus on Smart electricity grid research and less on the thermal grid.

3. Results from review of Smart Energy projects

Based on the analysis done for the Danish, Nordic and EU Smart Energy projects the conclusions about Smart Energy research and research gaps for each region are as follows:

Denmark

- The analysis shows that Denmark has a unique focus on Smart Energy systems and Smart Energy technologies compared to the other Nordic countries and Europe.
- The number of Smart Energy projects and granted funding has increased significantly since 2005, but in recent years the funding has slowed (see Figure 7).
- The funding for research and development projects has increased in recent years, as well as for demonstration projects, and funding in research projects has remained relatively constant in recent years (except for 2014) (see Figure 11).
- Most funding for the projects comes from the Innovation Fund Denmark, the ForskEL and EUDP programmes. Although the Innovation Fund Denmark grants the most money, the largest number of funded Smart Energy projects is from ForskEL and EUDP (see Figure 13 and Figure 14).
- 26 research areas were defined in this study about Smart Energy, these were split between the electricity, thermal and gas sectors. Out of a total of 26 possible research areas the average number of research areas per project reviewed in this study is between 2-3. The next highest number of research areas is 4-5 (see Figure 21).
- Funding in multi-sector research (electricity, gas and transport sectors) has increased in recent years and single-sector research has decreased (see Figure 16). Multi-sector research is more prominent in two-sector projects (see Figure 15).
- During the 10-year period there has been a predominant focus on the electricity sector in the single-sector projects, while the number of single-sector projects in the thermal sector and the gas sector have been lower, and this also means lower funding in these areas (see Figure 18, Figure 19, Figure 20).

- For projects that focus solely on non-technical aspects of Smart Energy very few projects (5 in total) and very limited funding has been dedicated (see Figure 15).
- In multi-sector projects the largest amount of funding is granted to the multi-sector projects that involve the electricity sector (see
- Table ***5*** and Figure 17).
- The four highest funded research areas are all in the electricity sector, the highest being for the Information and communication technology (ICT) research area, next highest for the development of appliances, followed by models and electricity infrastructure and systems (see Figure 22).
- Funding is limited in the area of energy ownership and about the role of institutions and organisations in Smart Energy (see Figure 22).
- In the thermal sectors funding is limited about the smart control of district heating (ICT/smart metering) (see Figure 22).
- In the gas sector funding is limited in the research areas - gas to CHP, electricity to fuel (gaseous or liquid) and gas infrastructures and systems (see Figure 22).

Other Nordic countries

- There appears to be a tendency for single sector focused projects focused on Smart Grid (electricity) in the other Nordic countries
- The number of projects and funding in Smart Electricity grids has increased significantly since 2005, but in recent years the funding has slowed (see, Figure 23 and Figure 24).
- Funding in research and development projects has been surpassed by demo and deployment projects in recent years (see Figure 24).

The European level

- There appears to be a tendency for single sector focused projects within Smart Grid (electricity) or thermal systems in the EU countries
- The number of projects and funding in smart electricity grids, transmission and distribution has increased significantly since 2005, but in recent years funding has slowed (see, Figure 34).
- The number of projects and project funding is mostly for smart electricity grids, followed by smart district heating and cooling and then energy storage (see Figure 32 and Figure 33).
- Funding for Smart electricity grids is split into three parts, grids, transmission and distribution and most funding has been granted for the grids part but the funding in these research areas is sporadic in the last 10 years (see Figure 26, Figure 27, Figure 28).
- Funding in smart district heating and cooling has been sporadic with peaks in funding in 2010 and 2013 (see Figure 29).
- Funding in energy storage has been sporadic with a peak in funding in 2012 (see Figure 30).
- Horizon 2020 calls are today more open to interpretation and enable applications that focus more on Smart Energy type projects (see more details in Section 3.7).

4. Gaps within Smart Energy research, development and demonstration

There are numerous research gaps in each energy sector, especially in the thermal and gas sectors. However, the most significant research gap is in the integration and interaction of different sectors, which is fundamental in a Smart Energy system.

The transition of the transport sector away from fossil fuels is a main concern in Smart Energy. However, there has been little research in this area in all the areas analysed, especially in terms of electricity to fuel which is expected to provide much of the transport fuel in the future, in the form of electrofuels.

There have been numerous feasibility studies carried out in Smart Energy. However, there has been negligible research into non-technical research projects that focus on ownership structures for non-traditional actors such as municipalities or communities. In addition, there has been limited research on how institutions and organisations will be involved in Smart Energy, for example municipalities and traditional energy companies.

Part A: Review of Smart Energy Projects

Denmark

The analysis in Part A for Denmark has been based on 225 Danish Smart Energy projects covering the electricity, thermal and gas sectors. The main conclusions from this analysis are as follows.

Overall in the last 10 years, the amount granted for funding in the Smart Energy area has increased significantly from negligible levels in 2005 to a cumulative total of 1,464 MDKK in 2015. In the last 10 years, the majority of projects in Smart Energy are research projects; however, in the last few years, the number of research projects has decreased and more research and development and demonstration projects have been funded. In fact, although there have been more research projects, the largest cumulative amount of funding has gone to research and development projects. This funding has increased significantly since 2011. And during this period, the research projects have remained at the same level of funding each year.

Most funding for the projects comes from the Innovation Fund Denmark and the ForskEL and EUDP programmes. Although the Innovation Fund Denmark grants the most money, the largest number of funded projects is from ForskEL and EUDP.

In the last three years, the number of projects that focus on a single sector has decreased and the number of cross-cutting projects with two or more sectors has increased (see Figure 2), and most multi-sector projects focus on two sectors.

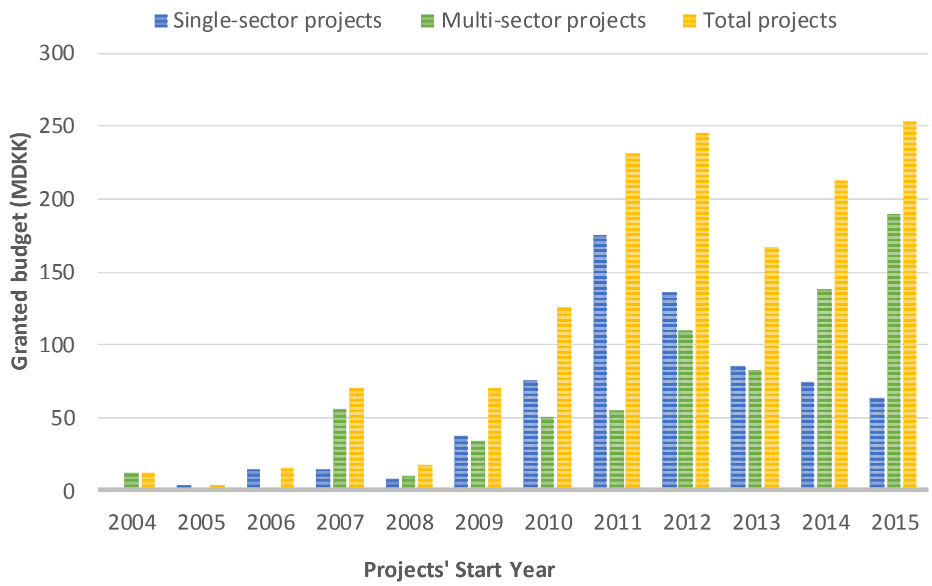

Figure 2: Distribution of granted budget, in MDKK, per year and per project type, i.e. single-sector projects and multi-sector projects. The total number of projects per year is also shown (2015 is not yet complete)

Most of the single-sector projects funded are in the electricity sector. However, the granted funding for single-sector electricity projects peaked in 2011 and more funding has gone to the gas sector in 2015 so far (see Figure 3). The thermal sector has received a very low level of funding in the single-sector projects in every year. When the electricity sector is included with another sector, the most funded combination is electricity and thermal sectors. However, the combination of the electricity sector and non-technical research has a large proportion of granted funding.

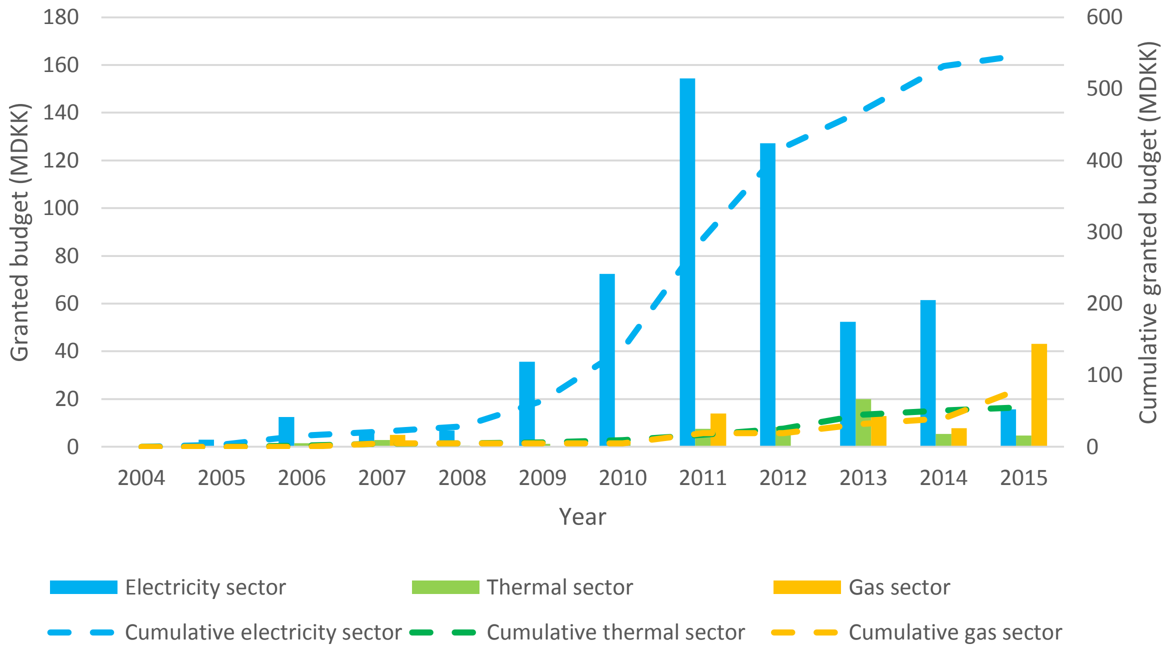

Figure 3: Annual granted budget per sector and cumulative budget from 2005 to 2015 per sector for single-sector projects (2015 is not yet complete)

There are only a few projects that focus on the non-technical aspects of Smart Energy alone. However, the funding allocated for the non-technical research areas in all the projects is around the same compared with the main energy sectors. The most funded non-technical research area is for feasibility studies. The lowest allocated funding is for the ownership research area.

Most projects investigate 2-3 sub-sectors out of a possible 26 sub-sectors included in this analysis. The most common sub-sectors in terms of instances researched are “Thermal infrastructures and systems” (thermal sector), “Development of appliances for smart systems” (electricity sector), and “ICT” (electricity sector). The most funded sub-sectors are “Development of appliances for smart systems” (electricity sector), “ICT” (electricity sector) and “models” (electricity). The most funded sub-sector in the thermal sector is “Thermal infrastructures and systems” and the most funded gas sub-sector is “Electricity to gas” and “Development of technologies”. On the sub-sector level in all the projects combined, the electricity sector has the highest funding (see Figure 4).

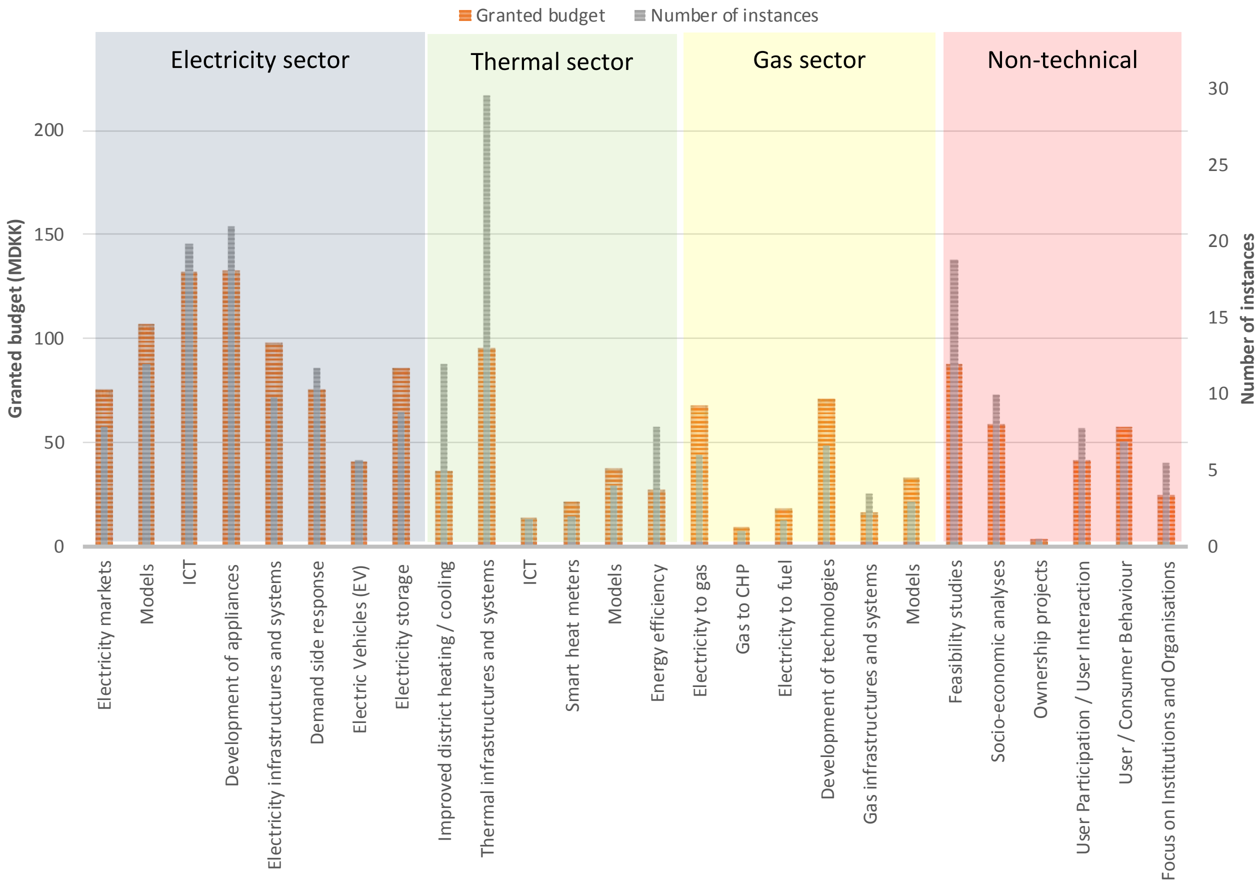

Figure 4: Cumulative granted budget (in MDKK) from 2005 to 2015 per sub-sector

Nordic region

For the Nordic region only smart electricity grid projects were included in the review. Based on a report from the Joint Research Council (JRC) 51 smart electricity grid projects were identified and reported as relevant from the smart energy system perspective [3].

The number of Smart Grid projects and budget spent in Norway, Sweden and Finland together is lower than the number of projects and funding for the corresponding projects in Denmark.

Sweden has focused more on demonstration and deployment (D&D) projects than Norway and Finland, almost 47% of the projects in Sweden are D&D projects and 66% of the budget is for these projects. Norway has the lowest share of D&D projects with 37% but has 52% of the budget allocated for these projects. Finland has only allocated 25% of the total budget for D&D projects even though their share of projects is 42%.

National cooperation within the smart electricity grid field has in Norway been organized in the network 'The Norwegian Smart Grid Centre', in Sweden in the 'Swedish Smart grid', and in Finland the Smart Grids and Energy Markets (*SGEM*) programme functions as such a network. A large number of RDD projects have been funded by either national research and energy agencies or by Nordic Energy Research. Some have achieved funding in relation to European collaboration.

The potential for using dynamic pricing eventually based on market or even spot market pricing has been the main engagement to move power usage (loads) to periods with surplus capacity. In addition, some projects have included local installations of heat pumps, solar panels and energy storage solutions mostly based on batteries, changing the role of households and company customers to become so called 'prosumers'

Several of the large-scale programmes have focused on developing and improving energy technologies within the classic fields of wind, solar, heating and gas. The Nordic Research Council has recently funded a number of projects from the Sustainable Energy Systems 2050 programme running from 2011 to 2015. Only few of these projects relate to the integration of energy sectors or Smart Grid developments. The Smart Energy cross-sectorial focus appears to be limited.

Europe

Also in Europe it appears that Smart electricity grids are in focus and that parts of the Smart Energy perspectives are less predominant. In Europe, 83 Smart Energy projects were identified through the data search on the SETIS database. From 2006 to 2011 the funding was steadily growing, where the highest funding occurred; however, from 2012, there was a drop in funding, though with a small increase in 2013. 2010 was the year with the largest amount of financing from the European Commission, but the largest project budgets were seen in 2013.

It is visible that the focus of most projects was on smart electricity grids (including distribution and transmission) with funding of ~440 MEUR and 49 projects and this research area is growing rapidly. In comparison to ~185 MEUR for smart district heating and cooling projects. The first smart district heating and cooling grids projects were funded in 2005 but there was no further funding until 2009.

Energy storage projects had a high share of 16 projects. These projects included electricity and heat storage at small, medium and large scales but most of the projects were focused on electricity. Out of 16 projects, 2 had the integration in energy systems as a focus. None of the projects has been identified as cross-cutting between electricity and liquid or gaseous fuels for transport, but there are 9 projects identified as relating to the integration of smart electric vehicles in the electricity grid. Under the Alternative transport fuel priority area there are also projects on fuel cells and hydrogen. 37 projects are under the main theme of Fuel cells and hydrogen with a total funding of 225 MEUR.

Compared to previous programmes, the Horizon 2020 Work Programme shifts focus towards greater integration and interaction of energy sectors, but at a limited level. The calls are purposely designed to be open for interpretation, thus not precluding certain research areas. This is a very important element to the text. In general, there are more calls written for Smart Grids focusing on electricity management. In terms of transport fuels, the focus is on new biofuels and advanced biofuels, and although no mention is made about finding synergies with other energy sectors to produce the fuels, for example using excess electricity to produce electrofuels, the call is open to interpretation and solutions.

Many individual smart electricity grid technologies have been developed during the last 15 years, but there is still a need for further market and service levels and the integration of electricity grids with other sectors. There have been few activities on the European level on the interaction between sectors, and this research needs to be targeted further in the new EU funding calls and political activities. There is a need for more focus on funding opportunities for projects that can offer a solution and have more cross-sectorial integration for the parts of the transport sector that cannot be electrified. Previous research efforts on the European level have been focusing on different types of energy storage but mostly on the efficiency and costs related issues. Further focus on the new storage technologies, their demonstration and cross-cutting storage research is necessary to achieve further efficiency improvements on the system level.

Part B: Smart Energy State-of-the-Art summary

In Part B the Smart Energy state-of-the-art research is described using knowledge from numerous experts in the field. Accordingly, the current research gaps are presented.

The state-of-the-art definition of Smart Energy is described as being - an energy system that enables cost-effective large-scale integration of fluctuating renewable energy (such as wind, solar, wave power and low value heat sources). It enables the energy system to achieve 100% renewable energy with low biomass demand and CO_2 emissions. It has a number of appropriate infrastructures for the different sectors of the energy system, which are smart electricity grids, smart thermal grids (district heating and cooling), smart gas grids and other fuel infrastructures. Through deep integration of these sectors, the system utilises new sources of flexibility such as solid, gaseous, and liquid fuel storage, thermal storage and heat pumps and battery electric vehicles.

A summary of the state-of-the-art research of the three main technical sectors in Smart Energy is presented below, as well as the gaps. The summary also presents the state-of-the-art of these sectors cross-cutting each other and the non-technical aspects of Smart Energy.

Electricity sector

In the electricity sector recent advances have considerably contributed to the reliability, and integration of intermittent energy from renewables. Modern distribution systems have been equipped with more and more power electronics interfaced dispersal generations, which makes the distribution systems more controllable. Other intelligent devices like smart transformers, energy storage systems, smart loads, etc. have also been applied to improve the overall efficiency of energy distribution.

In response to the system challenge of balancing demand and supply in an electricity grid increasingly based on intermittent renewable energy sources, a great number of projects have tested solutions for Demand Side Management in households. A specific challenge with involving households in the Smart Energy system is that they represent a large and diverse group of customers with low individual energy consumption. This makes it difficult to develop economically feasible schemes and services targeted households.

Electricity storage solutions based on synergies between the electricity, gas and thermal sector are being researched. Denmark is developing energy storage at the system level to increase the grid flexibility. The Power-to-gas (P2G) technology represents a megawatt-level energy storage solution to the problem of surplus energy from the renewables. Lithium batteries are also being researched as a large scale energy storage solution.

Despite these advances further research and development is needed in integrating the electricity sector with other sectors like thermal and gas since more possibilities are available than simply focusing on the electricity sector in isolation.

Further research is required focusing on: temporal and spatial correlation of renewable power generation; network congestions and energy curtailment in connection to the thermal and gas sectors; thousands of miles of energy transmission to the load centres which have huge network investments and large losses; and considerable mismatch between the offline simulation and the real time patterns from inaccurate predictions

Thermal sector

One main advantage of the thermal sector is that it provides a storage solution of energy. The thermal grid can contribute to the smart electricity grid by offering energy storage for surplus electricity (conversion by means of heat pumps) and by providing improved energy efficiency by allowing the utilisation of otherwise discarded heat, for example when using CHP for electricity production.

Recent studies' emphasise the role of district heating systems in building the future sustainable energy systems, however converting to a low-temperature district heating network is an essential need in order for interacting with low-energy buildings and integrating into Smart Energy systems. Recent advances in the thermal sector are in low temperature district heating systems, which enable for example higher penetrations of renewable energy and wider distribution of the systems.

The simulation of CHP plants is well described in literature. However, the challenges are in the daily operation and have not received much attention; but some studies have investigated strategies for the daily electricity trading of district heating plants. In recent years, a strong focus on mapping of heat demands in the form of heat atlases has been done.

The design of new low-energy buildings has been analysed and described in recent papers, including concepts like energy efficient buildings, zero emission buildings, and plus energy houses. Some papers address the reduction of heat demands in existing buildings and conclude that such an effort involves a significant investment cost. Consequently, an important question is to which extent these heat savings can be implemented in a future Smart Energy system with a significant share of district heating. It becomes important to identify the energy system's effect on savings, and possible synergies between various types of savings across different sectors. Energy savings need to be balanced with the possibilities to provide low temperature heat from renewable energy sources in future research.

Little work has been published on the development of optimization approaches for low energy buildings, which is mostly based on genetic algorithms or highly non-linear complex problems, including the modelling of the whole building together with the supply system.

Other important research areas to be further investigated are for example the concept of reversible heat pump/organic Rankine cycle reversible units coupled with advanced thermal storage. In addition, there is high potential for usable waste heat from industrial processes and from cooling processes in commercial buildings (e.g. supermarkets). There should also be more research done on enabling flexible integration of renewables between the energy sectors, for example between the heating and electricity sector.

In addition, future research should distinguish between different temperature levels since there is a significant difference between demands in different industries, for example for hot water, for comfort heating, comfort cooling, refrigeration, etc. Future solutions may have more pipelines carrying different temperature water.

Furthermore, research is required in large-scale heat pumps, low temperature district heating (in regards to its definition, temperature levels, connection with other technologies such as booster heat pumps, and influence from consumer hot water demand), network performance, improved district heating pipes, advanced monitoring, intelligent control, smart metering of heating and peak shaving, etc. A major research area is in the conversion process of the current district heating system to low temperature district heating and how this can be achieved.

At present the research about cooling demand is limited and there is little data available. A better understanding of the cooling demand is a prerequisite for more energy efficient solutions. District cooling is an area that should be researched further especially for buildings with a high cooling demand such as office blocks.

Numerous aspects of cooling in Denmark have been researched including the current and future cooling potentials (split into types of cooling and location), descriptions of existing district cooling and descriptions of the technical, financial and organisational solutions. Further research efforts should focus on how the current barriers to increase district cooling could be removed.

Gas sector

The gas grid is going to play an important role in the future renewable energy systems as today's natural gas network will have to adapt to different types of renewable gases. The gas grid can also contribute to the Smart Energy system by providing long-term energy storage of electricity through the conversion of power-to-gas and power-to-liquid. These conversion technologies are furthermore important as they enable the Smart Energy system to interact with those part of the transport system that cannot make use of electricity.

In current research it is unclear which gas infrastructures are needed in the long term. As an example it is uncertain what hydrocarbon will be used to meet the transport demands and whether it will be in gaseous or liquid form. Therefore, the question is, what kind of gases should be transported, stored and provide flexibility in a future smart energy system? The limits of transmission of hydrogen in the natural gas grid is connected to the pipeline materials, the properties of hydrogen and the facilities. More case studies that assess the impact of hydrogen and natural gas blending on the pipeline needs to be conducted including the costs analysis of managing hydrogen integration in the gas grid.

Different types of gases that can be a part of renewable energy system are biogas, synthetic gas (syngas), synthetic natural gas (SNG), hydrogen and CO_2. Biogas storage/SNG can be simply stored in large metal canisters that can ensure the proper pressure needed for storing these gases. Other available options are washed-out subterranean salt caverns, thick balloons or degassing tanks covered with flexible tarpaulins.

The Power-to-Gas (P2G) concept converts electricity to energy-rich gases hydrogen and methane. Hydrogen is the first product from the P2G process and can be used in industry or as a transport fuel if the infrastructure is developed.

While there are current well-functioning gas infrastructures for natural gas, and while this can provide flexibility in terms of supply, there is a need for further research in key decisions about gas infrastructures and storages. The main research gaps include gas for transport, carbon capture and recovery (CCR) for production of gases, electrolysers, gasification, electricity to fuels (gaseous or liquid), syngas and other gases and interaction of the gas grid with other energy sectors. Gas for transport will be extremely necessary for the green transition but further research and development in this field is required to determine which types of gases are needed and how they will be integrated with transport.

Cross-cutting of sectors

A future energy system based on renewable energy requires greater flexibility. This introduces greater complexity. This is not only in terms of intermittency but also in terms of the balance necessary between electricity and heat supply units such as CHP, power plants, and boilers. This becomes even more complex with the addition of mobility, fuels, and heat pumps, which are often necessary to create even more flexibility between the various sectors of the energy system.

Research on the integration of different energy sectors is vital and needs to develop in the next few years. The concepts developed so far do show this tendency but there is no large extent of literature that explores the interactions between different grids especially when the Power-to-Gas or Power-to-Liquid technologies are deployed.

In recent years some research has been done in this area. It has been shown that feasible storage and management of intermittent resources depend on sector integration and synergies among all parts of the energy and transport system. Smart Energy assessments have been carried out in Denmark to show how the entire energy system can use large-scale renewable energy and shift to 100% renewable energy systems.

Systematic methodology has been developed and applied to take into account the ability to handle key societal challenges and to thoroughly understand how the gaps in the current research trajectory can be eliminated. Coherent integrated scenarios have been done looking forward to 100% renewable energy in 2050 using integrated hourly energy system analyses.

In future research there needs to be a combined knowledge relating to the integration of renewable energy in the various sectors of the energy system, to minimise overall costs and fuel consumption (fossil or bioenergy). There is a lack of knowledge on (1) what does current research tell us about the integration of renewable energy by combining the different sectors and (2) what does the actual design of such a Smart Energy System look like?

A crucial element in Smart Energy is to show through coherent technical analyses how renewable energy can be implemented, and what effects renewable energy have on other parts of the energy system. Only four tools (EnergyPLAN, Mesap PlaNet, H2RES, and SimREN) have assessed 100% renewable energy systems using time steps of 1 hour or less. If the objective is to optimize the system to accommodate fluctuations of renewable energy the tool using 1-hour time steps are more beneficial than the other tools. Further development of these tools needs to be undertaken in order to make more accurate assessments, recommendations and developments in the transition to the Smart Energy system.

Research on the integration of the transport sector and other energy sectors is an urgent task. It enables utilising more intermittent renewable energy in both the transport and the electricity and heating sectors. It also enables a more efficient utilisation of the biomass resources without putting strain on the biomass resource. As mentioned above, a promising example of integrating the electricity, gas and transport sectors is through the Power-to-liquid concept. By converting electricity via electrolysis to hydrogen, then using the hydrogen either for boosting gasified biomass in the hydrogenation process or merged with CO_2 emissions, electrofuels can be produced. Previous research has shown that electrofuels are an important part of the future energy systems and that they can be used in the transport sector due to the bioenergy resource limitation. Electrofuels could provide a substantial amount of fuel for heavy transport. At present there are only two plants producing electrofuels based on CO_2 emissions.

Non-technical (Social, socio-economic and political dimension)

Non-technical analyses investigate how Smart Energy systems should be supported politically, economically and socially, and which kinds of institutional and organizational changes and learning processes are required in order to do so. The research theme is therefore strongly linked to and rooted in (Socio-Economic) Innovative Feasibility Studies and the development of Strategic Energy Planning (in Danish Municipalities).

A current institutional challenge concerns integrating the heat and electricity sectors. Geographically, Denmark is an interesting research area as a consequence of high renewable energy-share in electricity production combined with a well-established district heating sector.

The institutional models should address both investment decisions and subsequently daily operation decisions. Incentives should guide economic actors towards not only establishing the necessary infrastructure but also ensure a flexible operation of the individual parts in order to match the fluctuating supply.

Future electricity markets must be able to optimally deal with the dynamics and uncertainties of renewable energy generation, as well as with dynamic and flexible offers on the demand side. They should fairly re-distribute the increase in social welfare while providing enough returns to electricity producers for them to make appropriate investments.

Today's institutional structures do not adequately promote flexible and efficient integration of heat and electricity markets, which is a vital next step in the development of the smart energy system. The current tax structure in Denmark does for example not deliver the required incentive structure neither at the investment nor operation level. Future research should investigate various institutional models that could ensure the resource efficient integration between heat and electricity markets. Further, system benefits and costs which are not valued in current markets may have to be more systematically included in socioeconomic evaluation procedures. Updating and adjusting socioeconomic methodologies to the new technological paradigm constitutes an important research area for the years to come.

Citizens and other local actors to an increasing extent will be affected by and also participate in the transition towards a Smart Energy system in various ways. Municipalities, for instance, have been identified as key actors in the strategic energy planning of 100% renewable energy systems by the Danish Energy Agency.

Attempts to integrate households in the Smart Energy have so far been of limited success. From the system operators' point, the consumers are not as actively participating as expected. This raises the question whether the previous approaches to households have been relevant. Danish and international studies of Smart Grid demonstration projects indicate a need for a more nuanced understanding of the consumers (households) and their possible future role in the Smart Energy system, and to integrate/activate the consumer.

Research needs to investigate how the development of Smart Energy systems can improve the development possibilities of local citizens, local communities, and local businesses as well as local and regional authorities. There is an increasing requirement for concrete collaboration and coordination procedures between the state level, municipalities, producers and owners of renewable energy plants, consumers and producers of heat, biomass and power, and also in a learning process of the democratic base, the households.

Investigations need to be made on adequate ownership and investment models that, both, accelerate the implementation of Smart Energy system solutions, and improve the local and regional economy. Such research can be linked to wider feasibility studies and socio-economic analyses, in the sense that supporting local development through Smart Energy systems should also generate benefits at the central level for the state and society as a whole.

It has been found that it may be necessary to aggregate the demand flexibility of many individual end-users in order to make this flexibility operational in balancing the grid, and further research is needed in this area.

Security of energy supply is an essential research area in Smart Energy. System level analysis needs to be done on the seconds and minutes level in order to provide the resilient energy services with low risk, and which is also cost and resource effective. In relation to this, dispatchable capacity will still be needed in future Smart Energy systems based on variable RES, in order to have production capacity during periods with little or no production from variable RES. For this reason, a discussion is ongoing regarding how to ensure sufficient capacity of flexible dispatchable units.

Inter-organisational and interdisciplinary learning processes have so far not sufficiently been dealt with from a research point of view. It is in many of its aspects a new research area within the energy field. It is of profound importance systematically to develop principles for the design and implementation of this inter-organisational and interdisciplinary learning process, as an equal research theme synchronized with the development of Smart Energy system scenarios.

Abbreviations

AD	Anaerobic digestion
BIPV	Building Integrated Photovoltaics
BRP	Balancing Responsible Parties
CCPP	Cell Controller Pilot Project
CEESA	Coherent Energy and Environmental System Analysis
CEDREN	Centre for Environmental Design of Renewable Energy
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
DC	District Cooling
D&D	Demonstration and Deployment
DER	Distributed Energy Resources
DFIG	Doubly-Fed Induction Generators
DH	District Heating
DHC	District Heating and Cooling
DHN	District Heating Network
DHS	District Heating System
DHW	Domestic Hot Water
DKK	Danish Krone
DME	Dimethyl Ether
DSM	Demand Side Management
DSO	Distribution System Operator
DT	Decision Tree
EC	European Commission
EFP	Energiforskningsprogrammet (energy research programme)
ERKC	Energy Research Knowledge Centre
ESS	Energy Storage Solutions
ETL	Emission-To-Liquid
EUDP	Energiteknologisk udvikling og demonstration (research and demonstration for energy technologies)
EU	European Union
EV	Electric vehicle
FACTS	Flexible Alternative Current Transmission Systems
GIS	Geographic Information System
GWP	Global Warming Potential
HP	Heat Pump
HTL	Hydrothermal Liquefaction
HVDC	High Voltage Direct Current
ICT	Information and Communications technology
IDA	The Danish Society of Engineers (Ingeniørforeningen)
IEE	Intelligent Energy Europe
JRC	Joint Research Centre
LCE	Low Carbon Energy
LCPG	Low Capacity Power Generators
LPG	Liquefied Petroleum Gas

LTPG	Low-Temperature Power Generators
NG	Natural Gas
NGO	Non-Governmental Organization
NOK	Norway
ORC	Organic Rankine Cycle
P2G	Power to Gas
PMSG	Permanent Magnet Synchronous Generator
PMU	Phasor Measurement Units
PSO	Particle Swarm Optimization
PST	Phase-Shifting Transformers
PVT	Photovoltaic Thermal Hybrid Solar Collectors
R	Research
RDD	Research, Development and Demonstration
R&D	Research and Development
RE	Renewable Energy
RES	Renewable Energy Sources
SCWG	Super Critical Water Gasification
SE	Sweden
SEK	Swedish krone
SEP	Strategic Energy Planning
SETIS	Strategic Energy Technologies Information System
SGEM	Smart Grids and Energy Markets
SNG	Synthetic Natural Gas
SOEC	Solid Oxide Electrolysis Cells
SSA	Stability and Security Assessment
TED	Thermo Electric Devices
TEKES	Finnish Funding Agency for Innovation
TSO	Transmission System Operator
UK	United Kingdom
US DOE	The United States Department of Energy
WADC	Wide Area Damping Controllers
WAMS	Wide Area Measurement Systems
ZEB	Zero Energy Buildings

Introduction

The aim of this study is to investigate the research project tendencies in Smart Energy over the past 10 years in Denmark, the Nordic region and the EU in order to find gaps and to inform the Smart Energy Network's recommendations. The study also investigates the state-of-the-art in Smart Energy. This report forms the basis for an update/extension of the report: "*Roadmap for Forskning, udvikling og demonstration inden for Smart Grid frem mod 2020*" [1] from January 2013. In addition this report is in line with the "*Vision for Smart Energy in Denmark - Research, Development and Demonstration*" [4]. To fulfil this aim the project investigates:

- Past and current Smart Energy efforts
- Development tendencies on the Smart Energy domain
- Gaps within Smart Energy research, development and demonstration

In this report Smart Energy is defined as a cross-sectoral approach that makes use of synergies among the various energy sectors when identifying suitable and cost-effective renewable energy solutions. Its end goal is to achieve a high penetration of renewable energy in each sector in the energy system. The research done in this study takes point-of-departure from this definition and purpose. The report is split into two parts as shown in Figure 5 below.

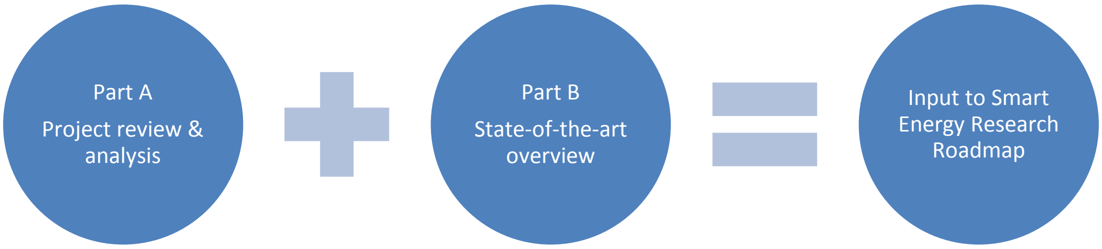

Figure 5: Relation between Part A and Part B. Part A is a collection of projects. Part B is a summary overview of the state-of-the-art

Part A is a review of research projects within Smart Energy with a focus on Danish, Nordic and European projects from 2005 to 2015. The purpose of Part A is to identify the current tendencies and research gaps in the Smart Energy project focus.

Part B is a review of state-of-the-art knowledge within Smart Energy based on expert knowledge. The purpose of Part B is also to identify research gaps, however here this is based on current expert knowledge of the Smart Energy state-of-the-art research from academia.

Part A: Review of Smart Energy Projects

Part A.1: Review of Danish Smart Energy projects

1. Review of Danish Smart Energy projects

In this part of the report a total of 225 Smart Energy projects are reviewed from Denmark in the period from 2005 to 2015. The review includes projects funded from all the main Danish funding bodies. It is assessed that the included projects represent over 95% or more of all the Smart Energy research projects in Denmark during this period. A database of the selected projects is made available for download as part of this report at www.vbn.aau.dk.

1.1. Methodology

1.1.1. Project selection criteria and process

The selection criteria used at the initial stage to identify research projects was whether they contribute to the implementation of Smart Energy or not. Using this selection criteria, the project selection did not include all renewable energy projects, but instead only projects that actually further develop, enable, enhance or implement Smart Energy by improving sector interaction or the possibility to do so.

The next step was a detailed mapping and labelling process outlining the characteristics of each individual project. For each Smart Energy sector, different sub-sectors were defined, covering Smart Grids, infrastructures and technologies for example. The transport sector is a major part of the energy system but in Smart Energy the relevant sub-sectors for transport arise under the electricity sector (i.e. EVs) and gas sector (i.e. electricity to gas, electricity to liquid fuels). The projects with non-technical aspects of Smart Energy (i.e. socio-economic, institutional) were also included. Some projects include technical and non-technical aspects.

Only projects that have started within the last 10 years (2005-2015) were included. In summary, the steps for selecting the projects were:

- An initial selection of the projects.
- Addition and exclusion of projects as the labelling, mapping and review process was undertaken.
- During the process a database with the research projects was developed and this was distributed and reviewed by members of the Smart Energy Network Partnership and other selected experts in the end of September 2015. The final database was distributed among the Smart Energy Networks Partnership by the end of October. As a result, a few projects were added to the database.

Projects included desk research projects, research and development projects and demonstration projects. In most instances the projects were selected based on a high level selection using the project abstracts available in the public databases, and on expert knowledge. The projects selected for the review are believed to serve as a very good representation of Smart Energy projects in Denmark. More than 95% of all Smart Energy projects are believed to be included, since all the largest funded projects were selected within the area and all major funding bodies have been screen.

1.1.2. Project funding bodies and selection process

The search and selection of projects was done using the online database www.energiforskning.dk [5], which includes projects funded by the following Danish funding bodies:

EUDP (Energiteknologisk udvikling og demonstration - research and demonstration for energy technologies)	• Part of the Danish Energy Agency • Supports and funds new energy technologies • Formerly EFP (Energy Research Programme)
forskEL	• Program of the Danish TSO Energinet.dk • Supports R&D and demonstration projects that contribute to the utilization of environmentally friendly electricity production technologies as well as the development of an environmentally friendly and secure energy system
Innovation Fund Denmark (Innovationsfonden)	• Invests in new knowledge and technology creating growth in Denmark • Formerly The Danish Council for Strategic Research
EU Framework Programmes (EU's Rammeprogrammer)	• Program of the European Union • Invests in Research and Innovation
forskVE	• Program of the Danish TSO Energinet.dk • Supports projects with the purpose of spreading and implementing small renewable technologies as photo voltaic, wave-energy, biogas and other RE based technologies into the electrical grid.
forskNG	• Program of the Danish TSO Energinet.dk • Supports biogas and bio-SNG R&D activities with relevance for the gas system
ELFORSK	• Part of The Danish Energy Association • Supports research and development in the field of efficient energy use at the end user

Additionally the website of the Danish Energy Agency [6] was used for searching projects funded under:

- Green Labs DK
- The Danish Energy Agency Strategic Energy Planning Pool (Energistyrelsens SEP Pulje)
- The Danish Energy Agency Strategic Energy Planning Green Super Pool (Energistyrelsens Grønne Superpulje)

Also other Danish websites and Danish funding programmes were taken into account for the selection of projects; among others: Gate 21 [7], the Danish District Heating Association [8], EFP, DONG Energy, the Danish Transport and Construction Agency [9], the European Regional Development Fund [10] and The Velux Foundations [11].

1.1.3. Overview of projects in the Danish energy database Energiforskning.dk

The Energiforskning.dk database [5] collects about 2,400 projects from various technological areas, with projects' start years spanning from 1995 to 2015. The last check of the database was made by the beginning of October 2015; thus, some of the projects that have been granted in year 2015 are not included in the database and hence are not part of this review.

The database categorizes all projects within eight technological areas (i.e., biomass and waste, hydrogen and fuel cells, energy efficiency, Smart Grid and systems, wind projects, solar projects, wave projects, and other), where each project is assigned to only one area.

Table 1 below shows the total number of funded projects within each technological area as well as the total budget and allocated granted budget, in MDKK, within the period 2005-2015. In this table, the year indicates granted year.

Table 1: Number of funded projects and granted budget in years 2005 - 2015. Available at energiforskning.dk database.

	Number of funded projects	Granted budget (MDKK)	Total Budget (MDKK)
Biomass and Waste	273	1,687	3,393
Hydrogen and Fuel Cells	177	1,444	2,813
Energy Efficiency	455	1,397	2,371
Smart Grid and Systems	127	9,70	1,635
Wind projects	159	1,012	1,788
Solar projects	149	547	1,240
Wave projects	52	169	285
Other	162	513	887
Total	**1,554**	**7,739**	**14,412**

Figure 6 presents granted budget per year for all technological areas. Note that the latest year is year 2014.

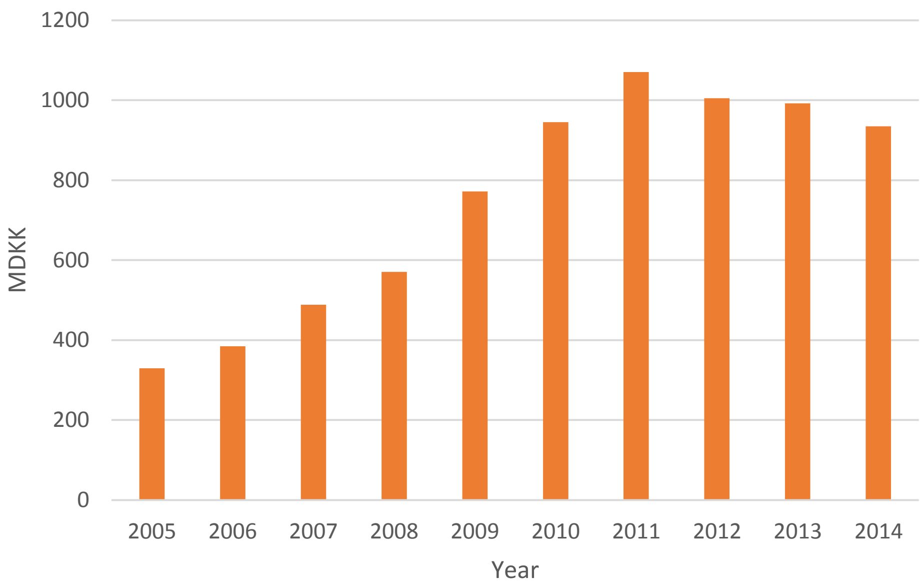

Figure 6: Granted budget per year for all technological areas. Source: www.energiforskning.dk

1.1.4. Selected projects

Table 2 presents the number of projects selected from the Danish energy research project Energiforskning.dk per technological area. Most of the projects within the technological area “Smart Grid and Systems” were selected, as most of them contribute towards the development of integrated energy systems. For the technological areas “Biomass and Waste”, “Hydrogen and Fuel Cells” and “Energy Efficiency”, only those projects with a smart systems component and focus were selected. None of the projects within the technological areas of “Wind”, “Wave” and “Other” have been selected as most of those projects cover specific technological development. One project of the technological area “Solar” was selected.

Table 2: Number of selected projects after the screening from www.energiforskning.dk and their corresponding budgets.

	Number of funded projects
Biomass and Waste, and Hydrogen and Fuel Cells	22
Energy Efficiency	55
Smart Grid and Systems	114
Wind projects	0
Solar projects	1
Wave projects	0
Other	0
Total	**192**

In addition to these 192 selected projects, the Danish District Heating Association (Fjernvarme F&U konto) has funded about 74 projects; of these 18 projects were selected for the database, which have an accumulated public funding of 9.5 MDKK. Also, 15 projects from SEP (Strategic Energy Planning) have been selected.

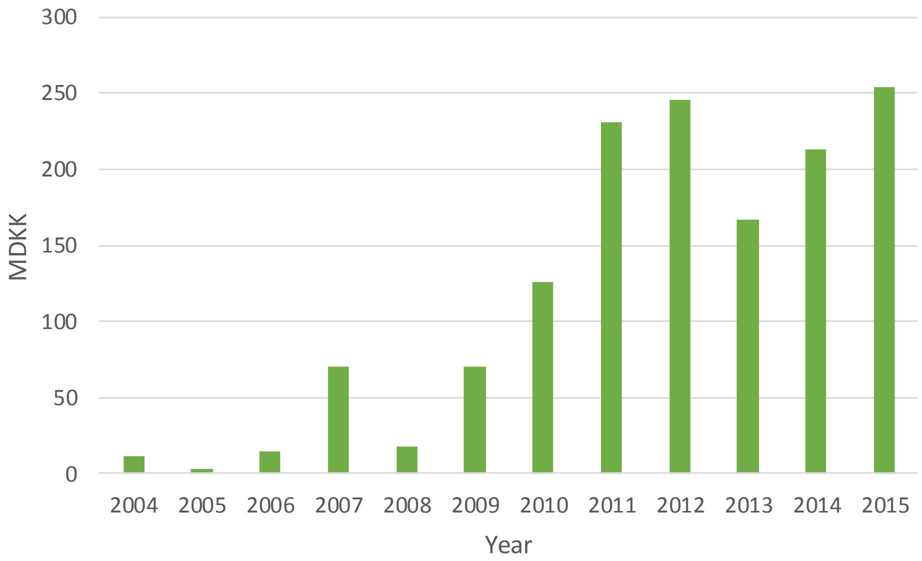

Figure 7: Granted budget per year for all Smart Energy projects selected in this study

Overall, 225 projects have been selected for the screening, which accumulate a total budget of 2,593 MDKK and a granted budget of 1,464 MDKK. The granted budget per year from 2004 to 2015 for all selected projects in this study is presented in Figure 7.

1.1.5. Labelling of selected projects

Once the projects were selected for review, they were labelled in an Excel database using the labels presented in Table 4. The labelling of the projects is based on the authors' best knowledge of the projects' nature. The database with all selected projects and the corresponding labelling of each project is publicly available.

The labelling is done in order to understand the character of the selected projects in more detail and their relation to smart energy sectors.

Firstly, the projects are tagged with the energy sector on which they focus, which may be more than one. Secondly, the projects are tagged with sub-sector focus areas, which may also be more than one. The first and second categorization together provides a detailed description of the energy sector focus of each project reviewed.

The labelling process has also included an exercise to identify whether a project deals with or covers predominantly one or more than one energy sector. To the question "*Is more than one energy sector considered in the project?*", the answer is either *Yes* or *No*. When the answer is *No*, the project is tagged with only one sector; and this is true for those projects that predominantly look into only one energy sector. When the answer is *Yes*, the project is tagged with more than one energy sector. Note that one project may cover two or more energy sectors; if this is the case the answer to the posed question is also *Yes*. Additional metadata was also used to label the projects and this is presented in Table 3.

Table 3: Project metadata

METADATA SCOPE:	Project scope	Project partners	Project nature	Project budget	Project period
METADATA ELEMENTS:	Stakeholders addressed	National (Danish)	Research (R)	Total budget (in MDKK)	Start year
	Geographical focus	International (EU)	Research and Development (R&D)	Granted budget (in MDKK)	End year
	Cities, Municipalities, Regions involved	Others	Demonstration Project	Funding Body	Number of years

Table 4: Energy system sectors and sub-sectors considered in the review of Smart Energy research projects

ENERGY SECTOR CONSIDERED:	**Electricity Sector**	**Thermal Sector**	**Gas Sector**	**Non-technical (Social, socio-economic, political dimension)**
SUB-SECTOR CONSIDERED:	Electricity infrastructures and systems (i.e. micro grids, charging infrastructure for EVs)	Thermal infrastructures and systems (i.e. heat storages, heat pumps)	Gas infrastructures and systems (i.e. gas sensors)	Feasibility studies
	Development of appliances for smart systems (i.e. heat pumps, electric boilers, new technologies, etc.)	Improved district heating (DH) and cooling	Development of technologies (i.e. electrolysers, biomass gasifier, biogas plant, etc.)	Socio-economic analyses
	Electricity storage (i.e. batteries, compressed air, pumped hydro, electricity to hydrogen, etc.)	ICT: control, algorithms, advanced monitoring	Electricity to gas (i.e. production cycle, upgrade of biomass or biogas)	Focus on institutions and organisations
	ICT: control, algorithms, communication, meters, protections	Smart heat meters	Gas to CHP (i.e. district heating)	User participation and user interaction
	Electric vehicles (EV) and other (i.e. electric boats)	Energy efficiency in thermal system (i.e. low energy houses, industrial surplus heat)	Electricity to fuel	User, consumer behaviour
	Demand side response, demand side management (DSM), flexible demand	Models (software tool)	Models (software tool)	Ownership projects
	Electricity markets and markets' design			
	Models (software tool)			

1.1.6. Division of granted budget between project sub-sectors

In most projects, numerous sub-sectors are researched from different energy sectors. For example, a project may focus on "electricity markets and markets' design" and "models (software tool)" in the electricity sector. Alternatively, a project may focus on these sub-sectors plus a sub-sector from a different energy sector, for example "ICT…" in the thermal sector. Despite this, only one total and granted budget is provided for the project. In order to analyse the budget per sub-sector, the budget has been divided equally between the different sub-sectors of a given project. For example, if a project researches five sub-sectors, the budget is divided by five among the sub-sectors. This is the most simple way to distribute the funds among sub-sectors and it is in line with the approach used by the Joint Research Centre (JRC) [3].

1.2. Results

This section presents the results of the study. For reasons of clarity, the results have been split into four parts. This enables us to make justified conclusions about the types of projects being funded and the sectors and sub-sectors being funded. The results show the current research tendencies and research gaps in Smart Energy. The results are presented in the following order:

Results 1: Nature of projects, i.e., number of research projects, granted budget for project types

- These results provide an initial overview of the types of projects being funded and how much money has been granted, and when, in the last 10 years.

Results 2: Level of funding per funding body, i.e., largest contributors to research projects

- These results show where the granted funding comes from and how much for all the projects combined.

Results 3: Sector division of projects, i.e., which sectors have the largest number of projects

- These results show which Smart Energy sectors have the largest number of projects and the extent of the budget per sector.

Results 4: Sub-sector divisions of projects, i.e., which sub-sectors have the largest number of projects

- These results show more in detail about the sub-sectors researched in the projects and how much funding is given to the different sub-sectors found.

All results for the granted budget assume that the total project budget is spent in the starting year.

1.2.1. Nature of projects

The nature of projects focuses on whether projects are research, research and development, or demonstration. These results do not provide conclusions on their own but they offer an overview of where project funding is being directed at in relation to Smart Energy research and where funding should go in the future.

The division of the total number of projects between research project, research and development (R&D) project, and demonstration project is shown in Figure 8 and Figure 9 below. If one project is included in two or more project types, then the project is split evenly between the project types and counts as half a project for example. This is also done for the granted budget for the project.

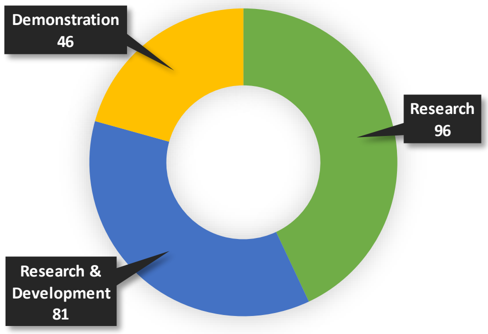

Figure 8: Distribution of Danish projects per project nature. Research projects are presented in green, R&D projects in blue, and demonstration projects in yellow.

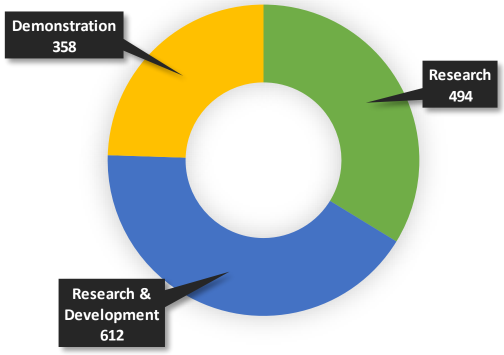

Figure 9: Distribution of Danish projects per budget (MDKK) per project nature. Research projects are presented in green, R&D projects in blue, and demonstration projects in yellow.

The results show that the research and R&D projects together comprise most of the projects. Most projects belong in the research category, but this is closely followed by research and development. The demonstration project category has the lowest number of projects.

Although there are fewer research and development projects these projects receive the largest share of the granted funding, followed by research and then demonstration projects.

The number of projects granted per year per project type is shown in Figure 10. These results provide more insight into how the project types have changed over the past 10 years.

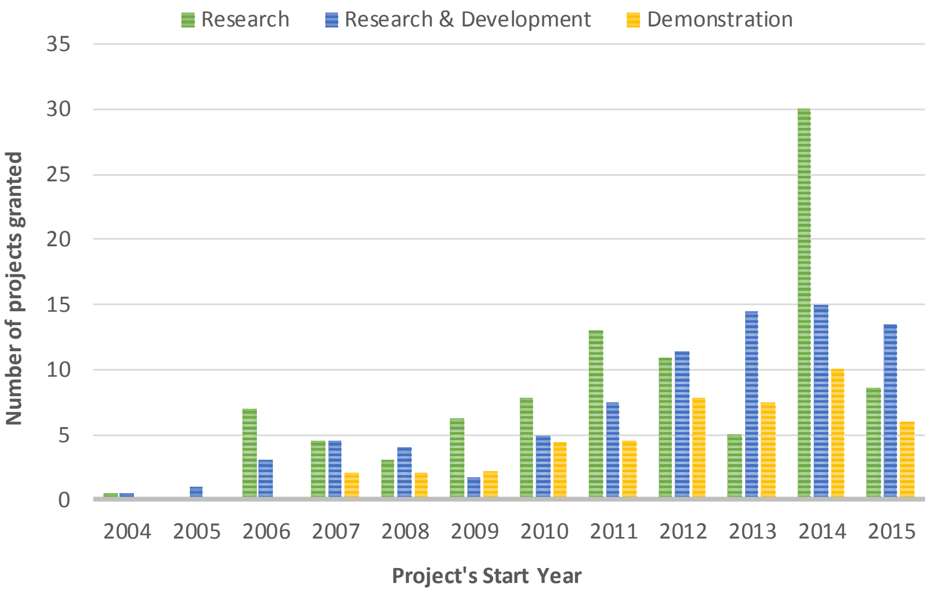

Figure 10: Distribution of Danish projects per year and per project nature (2015 is not yet complete).

As shown above, the total number of funded projects has increased steadily from year 2004/2005 to year 2014. All project types have increased per year, but the steadiest increase can be seen in research and development projects. Except for in 2014 when there was a spike in research project granted funding. The demonstration projects increased at a steady but slower rate. Since 2015 has not ended yet, the number of projects is lower than previous years. However, it appears that by the end of 2015 there will in general be fewer projects funded, as this data was taken in October 2015, near the end of the year.

It is also important to look into the granted budget per project since the number of projects does not always correlate with the amount of money funded. In Figure 11 below, the annual granted budget (in MDKK) per project nature is shown, while Figure 12 shows the cumulative granted budget.

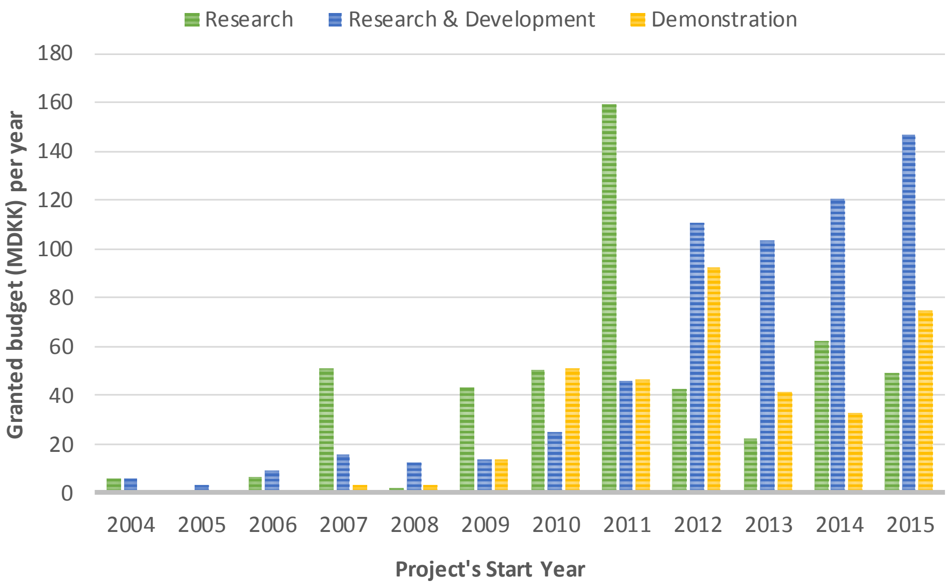

Figure 11: Distribution of granted budget, in MDKK, per year and per project nature (2015 is not yet complete).

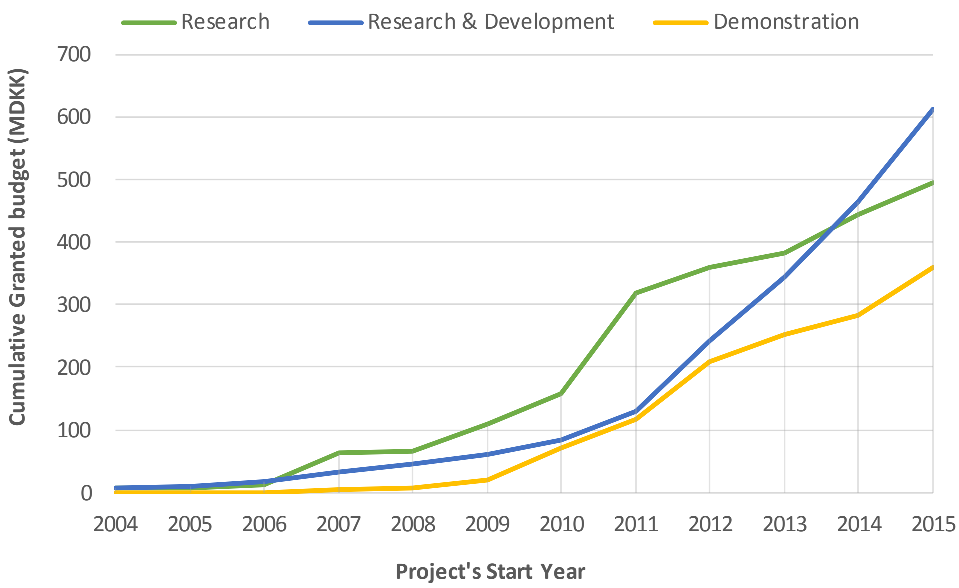

Figure 12: Distribution of granted budget, in MDKK, per year and per project nature (2015 is not yet complete).

In Figure 11, a similar pattern is shown as in Figure 10. The granted budget has increased steadily from year 2004 until 2015 for R&D projects. The granted budget for research projects has not increased as fast as the number of projects, except for 2011 when four large projects (iPOWER, CORPE, System services from small-scale distributed energy resources, and the Strategic Research Alliance for Energy Innovation systems (EIS)) were initiated with a combined granted budget of 150 MDKK. Although numerous research projects were initiated in 2014 the combined granted budget was comparatively not very high, indicating that the granted budget per project was lower in this year. The granted budget for demonstration projects has fluctuated in recent years with peaks in 2012 and 2015.

The cumulative granted budget (Figure 12) shows that research and development projects have accumulated the highest budgets of up to around 600 MDKK (over 10 years). The accumulated budget for research-only projects and demonstration projects show similar trends and are not increasing as steadily as research and development projects.

1.2.2. Level of funding per funding body

The selected Danish projects have received funding from numerous funding bodies including:

- ELFORSK
- The Danish Energy Agency Strategic Energy Planning Pool and Green Super Pool (presented as Energistyrelsen in the graphs below)
- EUDP
- ForskEL
- ForskNG
- ForskVE
- Innovation Fund Denmark
- Others including: the Danish District Heating Association, the Danish Energy Research Programme (EFP), DONG Energy, Green Labs DK, EU Framework Programmes, and the European Regional Development Fund

The number of projects funded by each funding body is presented in absolute numbers and in percentage in Figure 13 below.

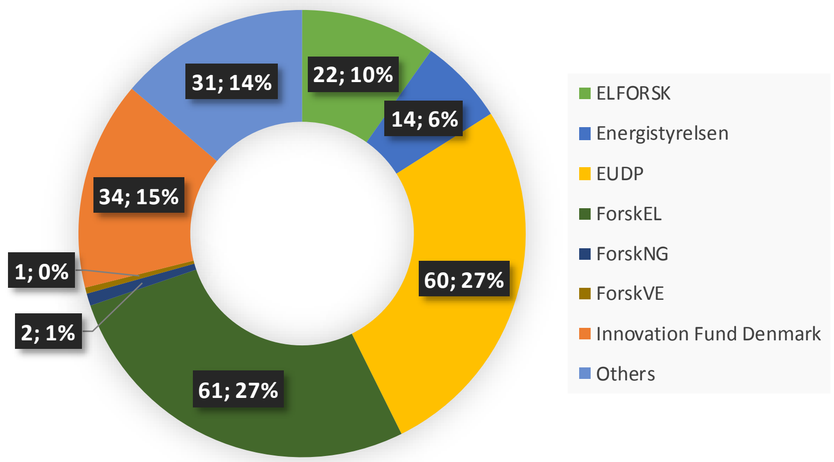

Figure 13: Number of projects funded per funding body in the analysis period, in absolute numbers and in percentage.

Combined, the projects from the programmes EUDP (in yellow) and ForskEL (in dark green) have funded just over half of the projects related to the development of Smart Energy. The next largest number of projects is funded by Innovation Fund Denmark.

The granted funding from each funding body is presented in Figure 14, which is shown in MDKK per funding body for all the projects between 2005 and 2015.

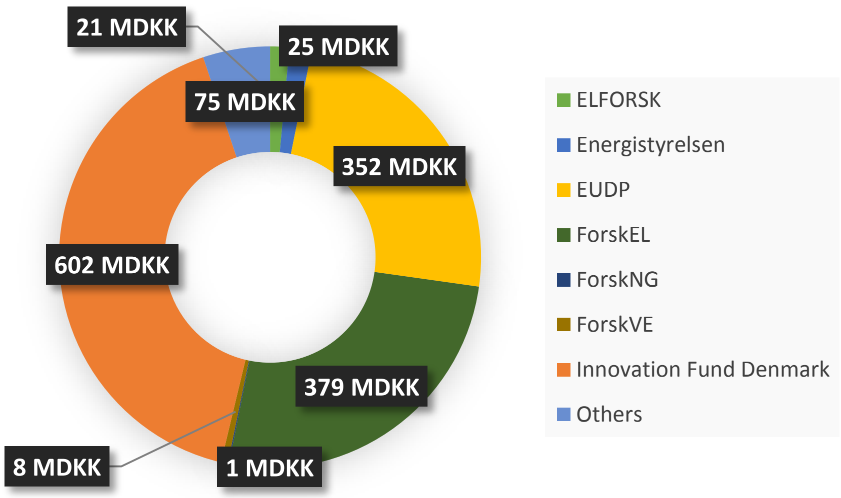

Figure 14: Granted funding, in MDKK, per funding body in the period of analysis.

The results show that Innovation Fund Denmark has granted the largest total budget (in orange), even though it accounted for only 15% of total number of projects funded. ForskEL (in dark green) and EUDP (in yellow) have the second and third largest funding, which is in line with the number of projects that they funded. The other bodies have granted much less than these three.

1.2.3. Sectors researched in the projects

In this section, the research content of the projects is analysed. As mentioned above, there are three main energy sectors defined in Smart Energy: electricity, thermal and gas. The projects are analysed in terms of their scope across these sectors.

Before analysing the specific content of the projects, we have first defined the number of projects that focus on a single energy sector or multiple cross-cutting energy sectors, as shown in Figure 15 below. The total granted budget (in MDKK) for project groups is also shown. In addition, Figure 15 illustrates those projects that focus only on social elements, and which do not specifically focus on any of the three energy sectors.

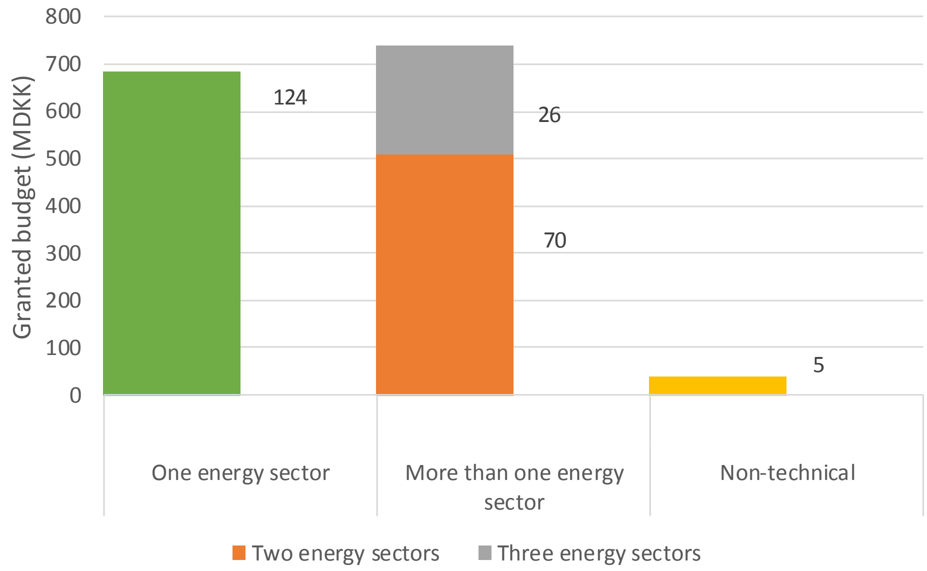

Figure 15: Number of projects that focus on one sector or numerous sectors included in the study

The results show that there are more projects with a single sector approach (124 versus 96 (multi-sector)). Most multi-sector projects focus on two sectors (70). There are five projects that focus only on non-technical aspects of Smart Energy and do not investigate any particular energy sector.

A different relationship is found for the granted budget. The largest grants are allocated to multi-sector projects, which accumulate to a total granted budget of 738 MDKK. The single sector projects have a total granted budget of 686 MDKK. The granted funding for the non-technical projects accumulates to 40 MDKK.

Figure 16 shows the annual granted funding for the single sector and multi-sector projects. The total granted budget for all projects is also shown.

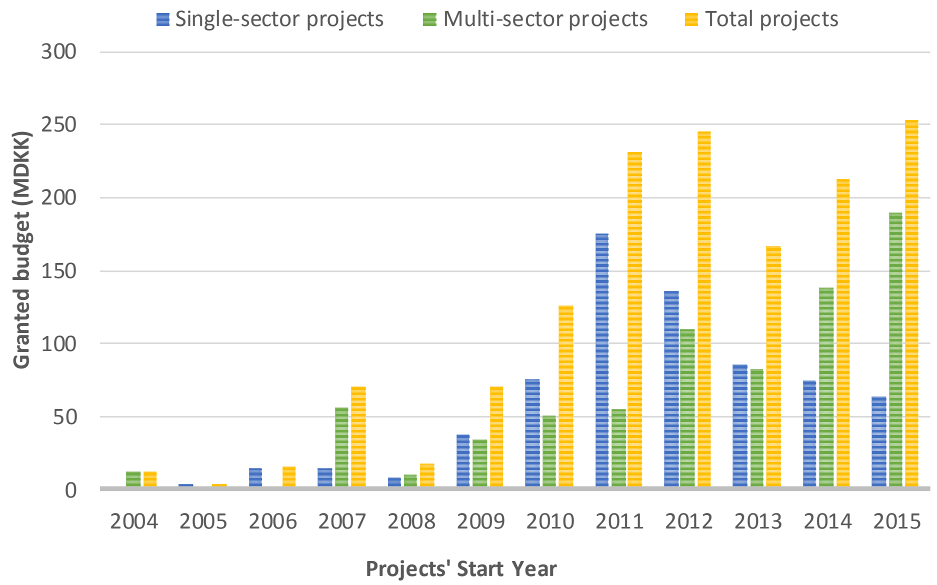

Figure 16: Distribution of granted budget, in MDKK, per year and per project type, i.e. single-sector projects and cross-cutting projects. The total number of projects per year is also shown (2015 is not yet complete).

As shown above, the granted budget for single-sector projects has increased from year 2008 to year 2012, but experienced a continuous decline since 2012. The multi-sector projects have seen an increase in years 2014 and 2015. The highest granted budget is achieved in 2015. The total granted budget for all projects has remained steady since 2011 except for a relatively large dip in 2013.

In

Table ***5*** and Figure 17 below, the granted budget that is given to each sector is shown.

Table ***5*** and Figure 17 present the same information; the table shows the absolute granted budgets and the figure is a visualization of the distribution of budgets among the sectors.

The purpose of these results is to show the amount of funding provided when an energy sector is part of a project with another energy sector. For example, the results show how much funding is granted to the electricity sector when its sub-sectors are researched with each other (cell in blue: 492 MDKK). And the results show the total granted budget when the electricity sector is researched in combination with sub-sectors from another sector (e.g., in green: 88 MDKK gas sector and electricity sub-sectors researched in the same projects).

As explained above, if a project investigates multiple sectors and sub-sectors the granted budgets of the projects were divided equally between the different sectors and sub-sectors.

Table 5: Granted budget (in MDKK) allocated to each energy sector and combination of energy sectors for all projects

Electricity sector	492			
Thermal sector	185	80		
Gas sector	88	31	135	
Non-technical	242	92	44	122
	Electricity sector	Thermal sector	Gas sector	Non-technical

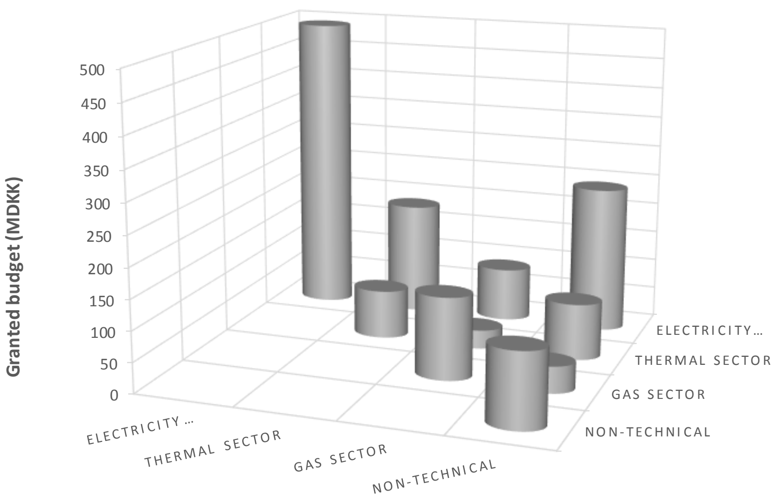

Figure 17: Granted budget (in MDKK) allocated to each energy sector and combination of energy sectors for all projects

As shown in the results, the sub-sectors of the electricity sector when researched in combination with each other have the greatest allocated granted budget. The second greatest budget is for the electricity sector in combination with non-technical (122 MDKK).

For a complete picture of the budget allocation among all the energy sectors and sub-sectors, a table is provided in Appendix A – Danish project results. This table illustrates the total budget divided into all the energy sub-sectors researched in all the projects.

1.2.4. Breakdown of energy sectors: Single energy sector projects

As shown above in *Figure 15*, in total there are 124 single sector projects. In Figure 18 below, the distribution of the different sectors between all the single sector projects is shown in terms of number of projects and granted project budgets.

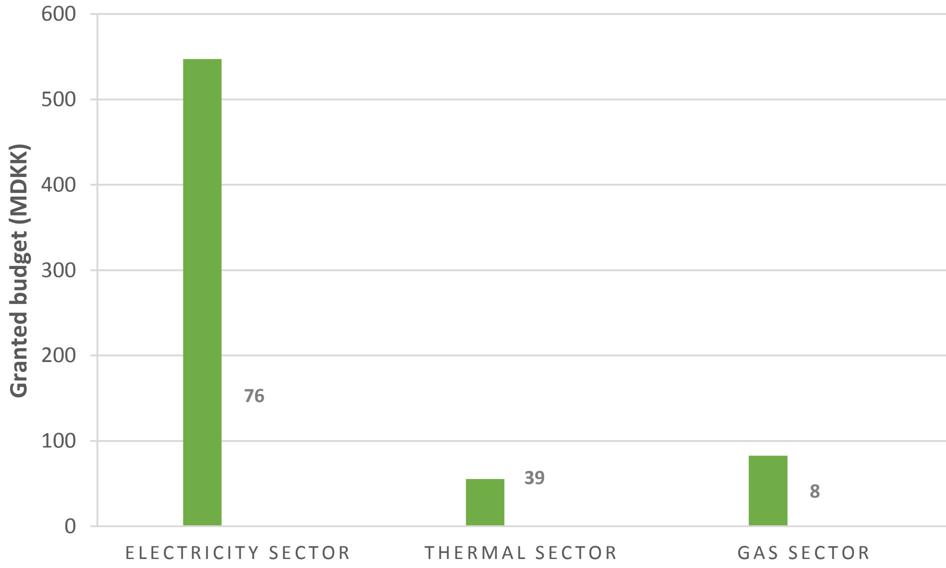

Figure 18: Number of single sector projects with focus on particular sectors

Of the 124 projects that address only one energy sector, 76 projects focus on the electricity sector. Although the thermal sector has 39 single sector projects, the granted budget for this sector is much lower; i.e., around 55 MDKK, whereas the electricity sector has a granted budget of around 547 MDKK. The gas sector has a higher granted budget than the thermal sector and this is because of some large projects such as Power2Hydrogen, El upgraded biogas and SYNFUEL.

In Figure 19 below, the number of single sector projects granted per year for each sector is shown.

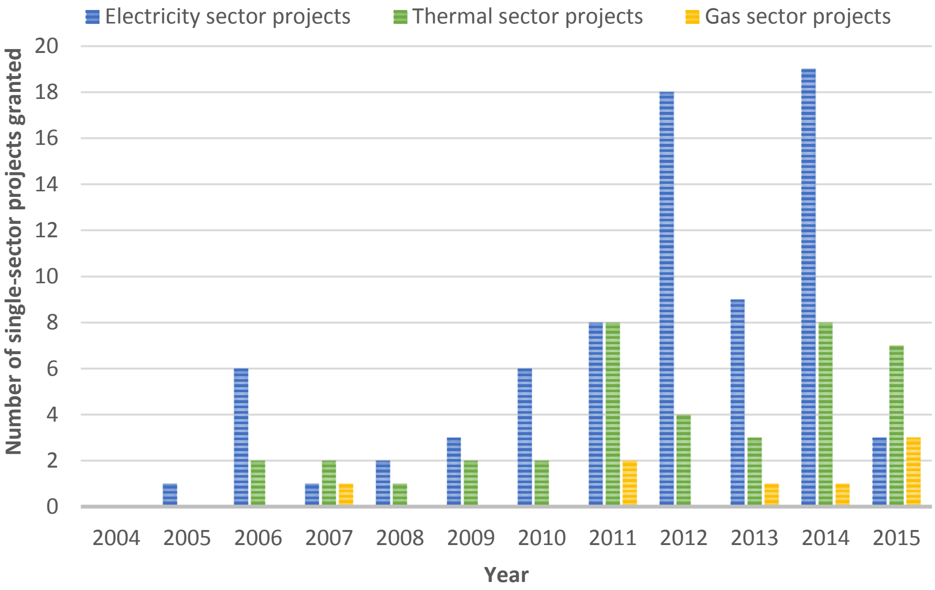

Figure 19: Level of number of single sector projects per year and per energy sector (2015 is not yet complete).

The results show that numerous electricity sector projects have been granted in the last few years, especially in 2012 and 2014. Less single-sector thermal projects have been granted, but in 2011, 2014 and 2015 the most projects were granted. Not many gas projects have been granted but 2015 was the year with most granted projects.

The annual granted budget per energy sector for the single sector projects are shown in Figure 20 below. The figure also shows the cumulative granted budget from 2004 to 2015.

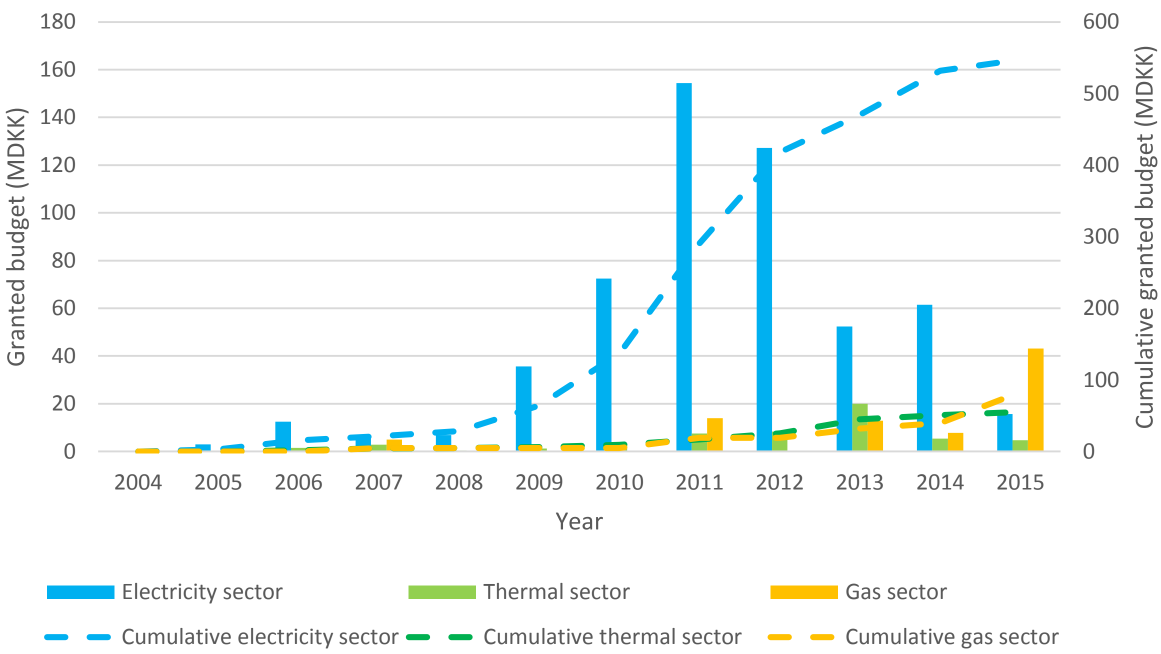

Figure 20: Annual granted budget per sector and cumulative budget from 2005 to 2015 per sector for single-sector projects (2015 is not yet complete)

The results show that the single-sector electricity projects had a higher granted budget in the years up to 2011 and since then the budget has decreased. The gas projects have increased over time, with a steeper increase in 2015. The thermal sector projects have remained at a low level of granted funding with small increase in 2013.

The cumulative granted funding has decreased in recent years but the reason why the budgets have decreased is likely because more projects include multiple-sectors in recent years and this is investigated in the next section.

1.2.5. Breakdown of energy sectors into sub-sectors

Three energy sectors have been defined for the analysis: electricity sector, thermal sector, and gas sector; where each sector is characterised by numerous sub-sectors (as presented in Table 4).

The aim of this research is to understand the distribution of energy sectors between the projects, but when more than one sector is involved it is complicated to compare projects. For example, the projects have numerous combinations of sectors, which makes them difficult to compare. Therefore, it is easier to analyse the projects on a sub-sector level. When the projects are analysed on the sub-sector level, the sub-sectors are compared. And this makes it possible to compare the multi-sector project sectors with each other.

In *Figure 21*, the number of projects and granted budget for projects with 1,2,3,4,5 or more sub-sectors is shown. This shows the scope of the projects when researching Smart Energy. There is a maximum of 26 sub-sectors possible in a project, as presented in Table 4.

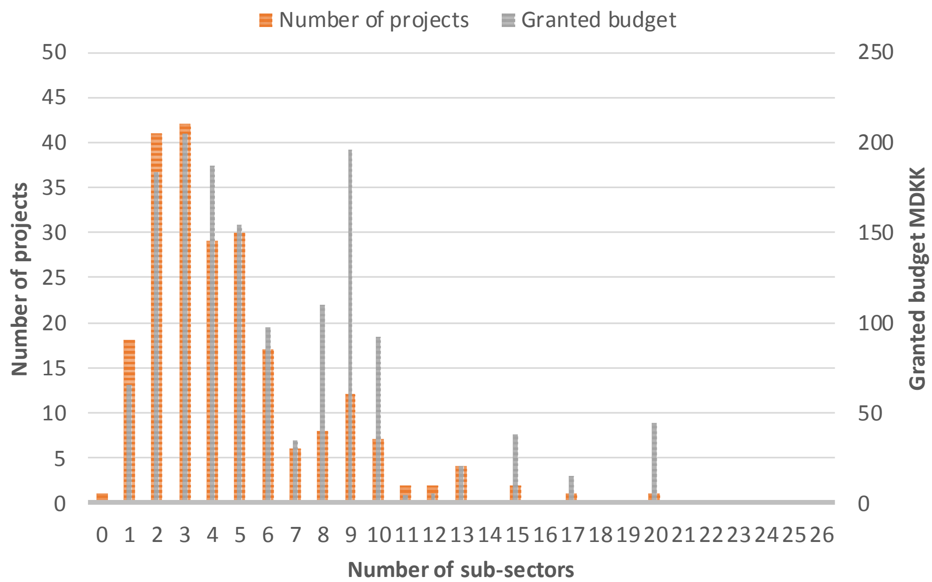

Figure 21: Number of projects and granted budget (in MDKK) dedicated to one, two, three, x,.. sub-sector projects

The results show that the number of projects with two to three sub-sectors are the most common of all the projects and subsequently these projects have the largest combined granted budget. The next most common projects have 4 or 5 sub-sectors. It is less common to have a project that focuses on more than 5 sub-sectors, or on only 1 sub-sector. The maximum number of sub-sectors in a project is 20; this is the CITIES project and it has a granted budget of 44 MDKK. The second largest project with a high number of sub-sectors (15) is the 4DH project with a granted budget of 37 MDKK. The projects with 9 subsectors have a large granted budget and the largest projects include iPOWER, Smart City Kalundborg, EDISON, Power2Hydrogen and TotalFlex and they have a combined granted budget of 112 MDKK.

In *Figure 22* below, the total granted budget for the different sub-sectors (and subsequently the sectors) for all the projects (single and multi-sector) is presented. Remember that the granted budget is split evenly between the sub-sectors in each project.

The electricity sub-sector is presented in blue, the thermal sub-sectors in green, the gas sub-sectors in yellow, and non-technical areas in red.

In some projects, there is focus on a single sub-sector and for each energy sector the results are presented in Appendix A – Danish project results.

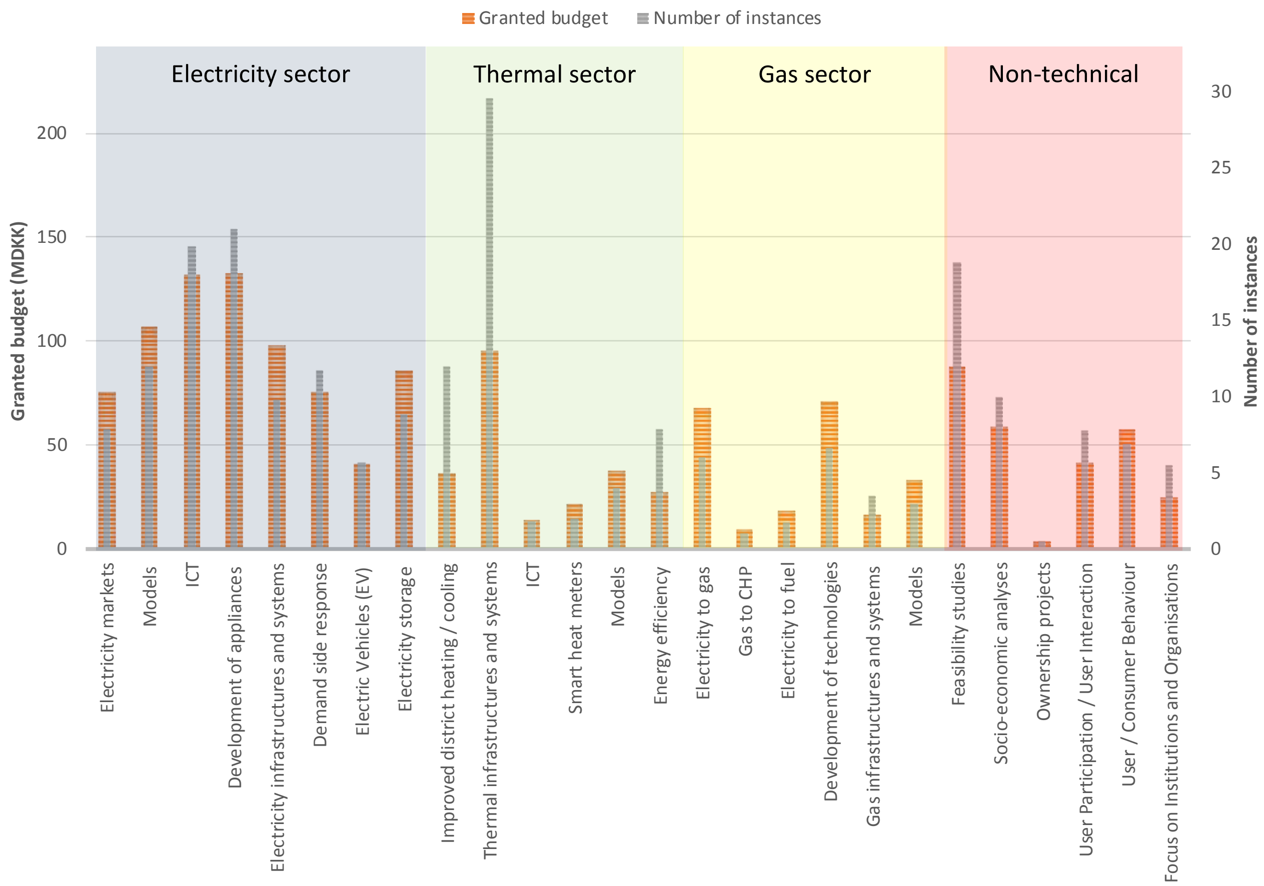

Figure 22: Cumulative granted budget (in MDKK) from 2005 to 2015 per sub-sector

As shown, most of the granted budget has been allocated to electricity sub-sectors, particularly to "ICT (information and communication technologies)" and to the "Development of new appliances for smart systems, such as heat pumps, new energy technologies, etc.". However, this is understandable since these sub-sectors occur numerous times in the projects. In the thermal sub-sectors, most of the funding has been allocated for the development of "Thermal infrastructures and systems (also including heat pumps)" and this sub-sector occurs in numerous projects. In the gas sector, the largest funding is given to "Electricity to gas" and "Development of technologies (e.g. biogas plant)". The projects with the largest funding in those areas include for example, "Electrogas - The renewable e-power buffer", "Power-to-gas via Biological Catalysis (P2G-BioCat)", "SYMBIO" and "SYNFUEL".

Numerous non-technical projects focus on “Feasibility studies”, “Socio-economic analyses” and User/Consumer Behaviour”. The research area “Ownership projects” occurs the least out of all research areas of all the projects.

1.3. Conclusions for the Danish projects

The analysis in Part A for Denmark has been based on 225 Danish Smart Energy projects covering the electricity, thermal and gas sectors. The main conclusions from this analysis are as follows.

- The number of Smart Energy projects and granted funding has increased significantly since 2005, but in recent years the funding has slowed (see Figure 7).
- Funding in research only projects has seen a decrease in recent years (except for 2014) as it is surpassed by research and development, and demonstration projects (see Figure 10).
- Most funding for the projects comes from the Innovation Fund Denmark, the ForskEL and EUDP programmes. Although the Innovation Fund Denmark grants the most money, the largest number of projects funded is from ForskEL and EUDP (see Figure 13 and Figure 14).
- The average number of research areas is between 2-3 out of a total of 26 potential research areas defined in this study. The next highest number of research areas is 4-5. Not many studies investigate more research areas than this (see Figure 21).
- Funding in multi-sector research (electricity, gas and transport sectors) has increased in recent years and single-sector research has decreased (see Figure 16). Multi-sector research is more prominent in two-sector projects (see Figure 15).
- The number of projects and especially the amount of funding in single-sector projects for the thermal sector and the gas sector has been less than the electricity sector during the 10-year period (see Figure 18, Figure 19, Figure 20).
- For projects that focus solely on non-technical aspects of Smart Energy very few projects (5 in total) and very limited funding has been dedicated (see Figure 15).
- In multi-sector projects the largest amount of funding is granted to the multi-sector projects that involve the electricity sector (see
- Table ***5*** and Figure 17).
- The four highest funded research areas are all in the electricity sector, the highest being for the ICT area, next highest for the development of appliances, followed by models and electricity infrastructure and systems (see Figure 22).
- Funding is limited in the area of energy ownership and about the role of institutions and organisations in Smart Energy (see Figure 22).
- In the thermal sectors funding is limited about the smart control of district heating (ICT/smart metering) (see Figure 22).
- In the gas sector funding is limited in the research areas - gas to CHP and gas infrastructures and systems (see Figure 22).

Part A: Review of Smart Energy Projects

Part A.2: Review of Nordic Smart Energy projects

2. Review of Nordic Smart Energy projects

There has been a rather intensive and large activity in all Nordic countries concerning Research, Development and Demonstration (RDD) in the field of Smart Grid research during recent years. In all countries, this field has also resulted in the creation of national cooperation within networks of actors involved in Smart Grid research and experimentation. This review has a focus on the Nordic countries, Norway, Sweden, and Finland, as the research activities in Denmark are reported in Section 0.

The JRC [3] has reported 97 projects related to the smart electricity grid theme and in this section, 51 of the projects have been identified and reported as relevant from the smart energy system perspective. The list of reviewed projects can be seen in

Appendix C – Selected Nordic projects.

The number of Smart Grid projects and budget spent in Norway, Sweden and Finland together is lower than the number of projects and funding for the corresponding projects in Denmark. It is visible from Figure ***23*** that Sweden had focused more on demonstration and deployment (D&D) projects than Norway and Finland, almost 47% of the projects in Sweden are D&D projects and 66% of the budget is for these projects. Norway has the lowest share of D&D projects with 37% but has 52% of the budget allocated for these projects. Finland has only allocated 25% of the total budget for D&D projects even though their share of projects is 42%.

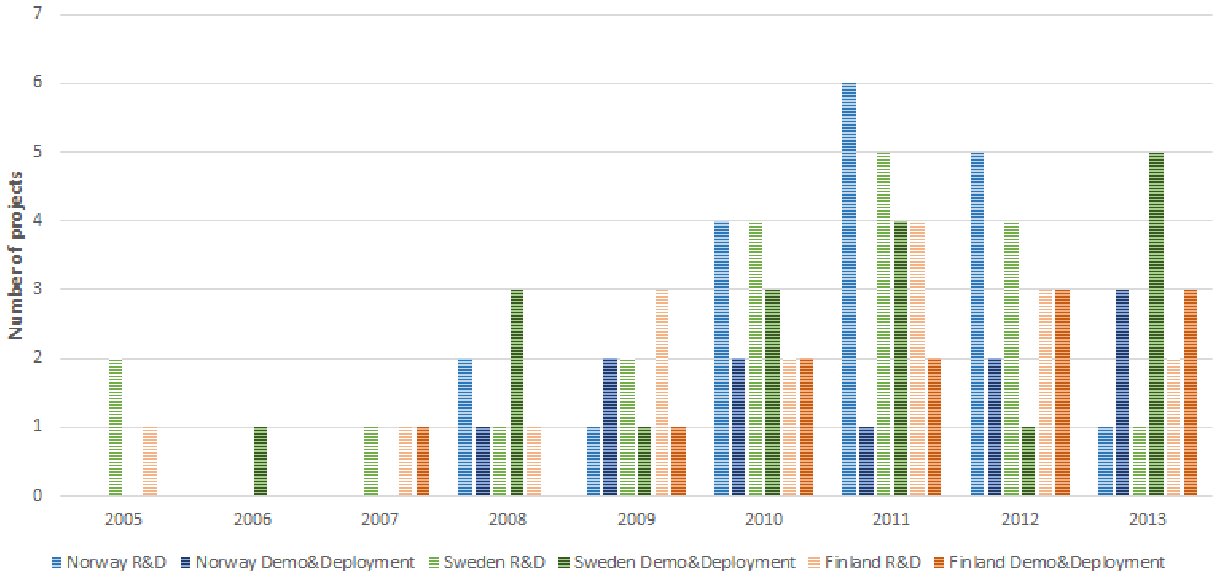

*Figure 23. Number of R&D and Demo & Deployment projects from 2005 to 2013 for Norway, Sweden and Finland. *Data from* [12].

The total budget for all three countries is presented in Figure 24. Approximately half of the budget is allocated for R&D projects and the other half is for D&D projects. The total budget for all three countries in the period from 2005 to 2013 was 222 MEUR. The graph assumes that the entire budget is allocated in the starting year of the project. Having this in mind, the largest funding was in 2011 and funding has been decreasing since then.

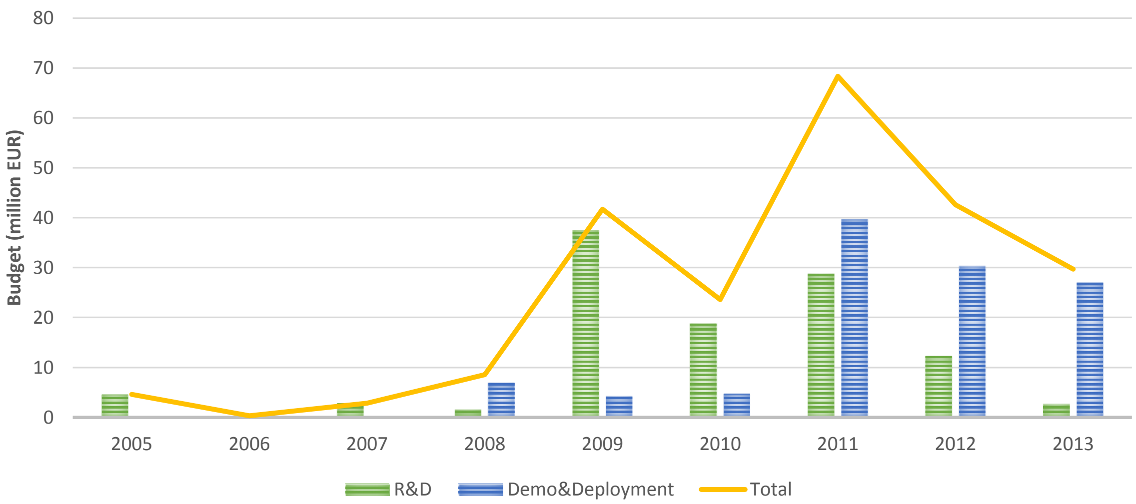

*Figure 24. Budget for Smart electricity grid projects for Norway, Sweden and Finland from 2005-2013 divided into R&D and D&D. *Data from webpage: http://ses.jrc.ec.europa.eu/european-smart-grid-projects-number-and-budget-evolution*

National cooperation within the smart electricity grid field has in Norway been organized in the network 'The Norwegian Smart Grid Centre'[13], in Sweden in the 'Swedish Smart grid' [14], and in Finland the Smart Grids and Energy Markets (*SGEM*) programme functions as such a network. A large number of RDD projects have been funded by either national research and energy agencies or by Nordic Energy Research. Some have achieved funding in relation to European collaboration.

The focus in the Nordic countries concerning Smart Grids differs not least in terms of which energy sources have dominated the electricity production until now. Norway has almost solely been supplied by hydropower, while Sweden has hydropower and nuclear as almost equal suppliers, and Finland is dominated by wood, coal and nuclear with some imported energy from Russia. Where in Norway the export of electricity from hydropower must be developed by, e.g., balancing in relation to the inclusion of more wind energy and the need for electricity for transport, Sweden and Finland still depend on a dominant backbone of other fuel sources for power production. It is obvious from the review that smart electricity grid perspectives have been limited to the two-way information aspect of smart metering. The potential for using dynamic pricing eventually based on market or even spot market pricing has been the main engagement to move power usage (loads) to periods with surplus capacity. In addition, some projects have included local installations of heat pumps, solar panels and energy storage solutions mostly based on batteries, changing the role of households and company customers to become so called 'prosumers'.

Apart from these projects, which have had the focus on balancing the grid with varying production from wind turbines, solar panels and through price mechanisms, several of the large-scale programmes have also been focused on developing and improving energy technologies within the classic fields of wind, solar, heating and gas. The Nordic Research Council has recently funded a number of projects from the Sustainable Energy Systems 2050 programme running from 2011 to 2015. Only few of these projects relate to the integration of energy sectors or Smart Grid developments.

Partly based on funding from the Oil and Energy department, Norges Forskningsråd has provided funding for research and innovation through the RENERGI programme that in total has spent around 2 billion NOK in the period from 2004 to 2012. This programme has been followed by a new programme, ENERGIX, that is operational from 2013 to 2022.

The RENERGI programme was structured in sub-programmes that focus on: (1) de-central production and integration (which include Smart Grid projects supported with approx. 140 million NOK); (2) energy use in transport; (3) support to research centres on renewable energy transformations (e.g., the CENSES centre); (4) support to off-shore wind technology; (5) solar power; (6) energy efficiency of buildings and industry; (7) wave power; (8) heating and cooling technologies including heat pumps and geothermic, and (9) biomass utilization and bio fuels.

The follow-up programme ENERGIX is funded by several departments besides Oil and Energy and includes Transport, Environment, Agriculture, Education and Fishery. The programme has been re-oriented to focus more on energy policy, economy, market design, new concepts, and the integration and management of the energy system both at national and international scale. Besides these overarching topics focus is on traditional research and innovation activities concerning renewable energy technologies, energy savings, and conversion.

In Sweden, the research programmes SweGRIDS and ELEKTRA have supported Smart Grid projects. ELEKTRA is funded by the Swedish Energy Agency and some contribution from industry investing 80 million SEK from

2013 to 2017. Its focus is on sustainable transition of energy systems, reduction of power failures and energy efficiency. SweGRIDS is a co-operation between universities, ABB and Vattenfall and focuses on research funding.

Alongside the funding of research and innovation projects, rather large support programmes have been established that support demonstration and also investments in renewable energy solutions. In Norway, the government agency ENOVA established in 2002 has been providing investment support by refunding about 25-35% of investments in private households as well as companies that invest in renewable energy production, solar panels, heat recovery, heat pumps, charging stations for electrical vehicles, and energy efficiency of buildings.

In Norway, a strong focus and support has been given to electric cars and the electrification of transport which not least shows in the sales of electric cars where Norway has the highest proportion in Europe. This can also be seen in the support for research in this field like the funding from the Transnova programme that supports, in almost equal proportions, projects about electrification, bio fuels and hydrogen. An important part of this endeavour is focused on the building of the needed infrastructures, standards and concepts for charging/fuelling the cars.

In Sweden, the government agency Energimyndigheten has since 2008 also funded large-scale demonstration projects of which some also have received funding from the EU NER300 support programme for commercial demonstrations of renewable energy systems including the fields of bio-energy, solar energy, geothermic energy, wind power, wave power, Smart Grids as well as carbon capture and storage. The total support is in the magnitude of some billion SEK with total project costs of 7-8 billion SEK.

Though the KIC InnoEnergy is an EU sponsored initiative it does play a specific role in the Swedish (and European) Smart Grid activities as it has been coordinating the Smart Grid and storage parts of this consortium. In general, the consortium is focusing as much on efficient use of fossil fuels and nuclear as on renewable energy and energy efficiency of buildings, cities and processes.

Three Finnish research programmes: CLEEN, EVE, and Innovative Cities funded and run by TEKES have been instrumental in the support for Smart Grid activities, though these have not been the core of either programme. Compared to the other Nordic countries, Finland does not have an explicit formulated policy for Smart Grid developments. In the CLEEN programme, the funding amounts to 40 MEUR. This amount is used for the funding of different aspects of energy technology and innovation. Within this framework, the 'sgem' programme works with customer engagement and demand response, network capacity and management, distributed resources (local generation like solar, wind, heat pumps, etc.) as well as electric vehicles and energy storage.

Support to Smart Grid power generation, grid integration and demonstration of solutions that include the integration of wind power, energy storage and distributed production is covered in a sub-programme of the Innovative Cities programme.

The EVE programme has been operating in the period from 2011 to 2015 with a budget of 100 million EUR used to support research and innovation.

Some of the support to the production and investments in renewable energy is given through, e.g., feed-in tariffs for larger wind turbines and investment support for off-shore pilot projects. In parallel to, e.g., Denmark, Finland has a high degree of combined heat and power plants where policies attempt to support their conversion to wood based fuels.

Selected sources and overview of presentations and reports on this subject: [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25] and [26].

Part A: Review of Smart Energy Projects

Part A.3: Review of European Smart Energy projects

3. Review of European Smart Energy projects

Energy research in the European Union is driven by Energy and Climate policies in places that have targets for 2020 and visions up to 2050. In order to meet these targets, sets of funding bodies and programmes were formed to provide funds for projects that can transform the European energy system to future low carbon technologies. The Energy Research Knowledge Centre (ERKC) identified 45 themes as important for policy makers and researchers. These themes were divided into 9 priority areas of which some have aspects of smart energy systems. ERKC has made a small progress in using a different terminology than previously. They do not define Smart Grids as smart electricity grids but include both smart district heating and cooling, both demand and supply side, and storage options. This is an important step forward as the future energy systems will be built upon different Smart Grids, not only smart electricity grids.

The scope of this section is to give an overview of the EU-funded projects in different smart energy system areas and to see the trends in funded projects. The section includes 83 projects that were identified through the data search on the SETIS database [27].

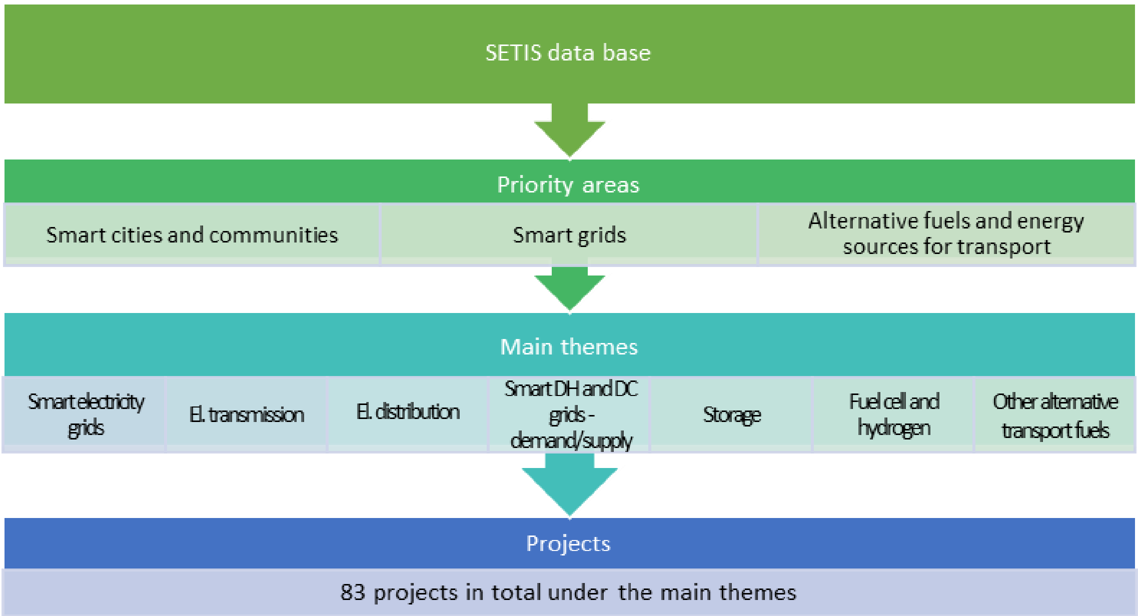

Figure 25. Methodology applied for funding overview in different themes

The search focused only on the main themes of interest under the specific priority areas. Therefore, this overview includes the priority areas *Smart grids* and *Smart cities and communities* including smart electricity grids, transmission and distribution of electricity, smart district heating and cooling grids, both demand and supply side, and energy storage. The transport sector projects were identified from the priority area *Alternative fuels and energy sources for transport* and only the theme *Other alternative transport fuels* was included. There is no specific focus on the gas grid infrastructure in any of the 9 priority areas; therefore, an overview of the smart gas grid projects is not included.

The process of the search is outlined in Figure 25 and only projects that had the main theme indicated in the database, as the ones mentioned above, were taken into consideration. Under Thematic Research Summaries [28], a total list of projects that relate to the specific themes is presented and the list also includes cross-thematic projects that are of some relevance to the themes. The time frame for project search was the period 2005-2015; hence, funds included are FP7 funds, Intelligent Energy Europe (IEE) and other European

Commission funds. No Horizon 2020 funded projects are included as they have not yet been registered in the SETIS system [29]. The project funds are shown under each category apart from transport, with an indication of the time period, the total allocated grant from the EU, total project budget and total private/other funding for each project. The funds are assigned to the starting year of the project.

The limitations of this project overview are that it has focused only on the main themes and it does not necessarily give the full overview of the projects related to specific topics. Moreover, it completely excludes the projects related to gas grids, as this is not an existing theme in the used database. However, the overview demonstrates the overall tendencies of the funded projects in different areas and this led to the identification of some projects with an integrated system approach.

3.1. Smart Electricity grids

Smart electricity grids are defined as "*electricity networks that can efficiently integrate the behaviour and actions of all users connected to it in order to ensure an economically efficient, sustainable power system with low losses and high quality and security of supply and safety*"[30]. They belong under the priority area of Smart Cities and Communities as they are seen as an integral part of the smart city concept. The projects under this specific theme include research in devices, software and services for network-user communication, demand side management, integration of distributed energy resources, network performance, etc. The theme can be subdivided into: integration of smart consumers, integration of smart metering, integration of distributed energy resources (DER) and new uses, and smart distribution network. 26 projects have been identified under this main theme. These projects can be supplemented with projects under smart electricity transmission and smart electricity distribution. In 2014, JRC published a detailed overview of all smart electricity grid projects including national, private, regulatory and EC funding[3]. It is important to point out that the project overview presented here includes only funding from the European Commission and projects that are under the main theme of smart electricity grids, smart electricity transmission and distribution.

From 2002 to 2013, the European Commission has invested 112 MEUR in these 26 projects as shown in Figure 26. The funding was steadily growing from 2006 to 2011, where the highest funding occurred; however, from 2012, we can see a drop in funding, though with a small increase in 2013.

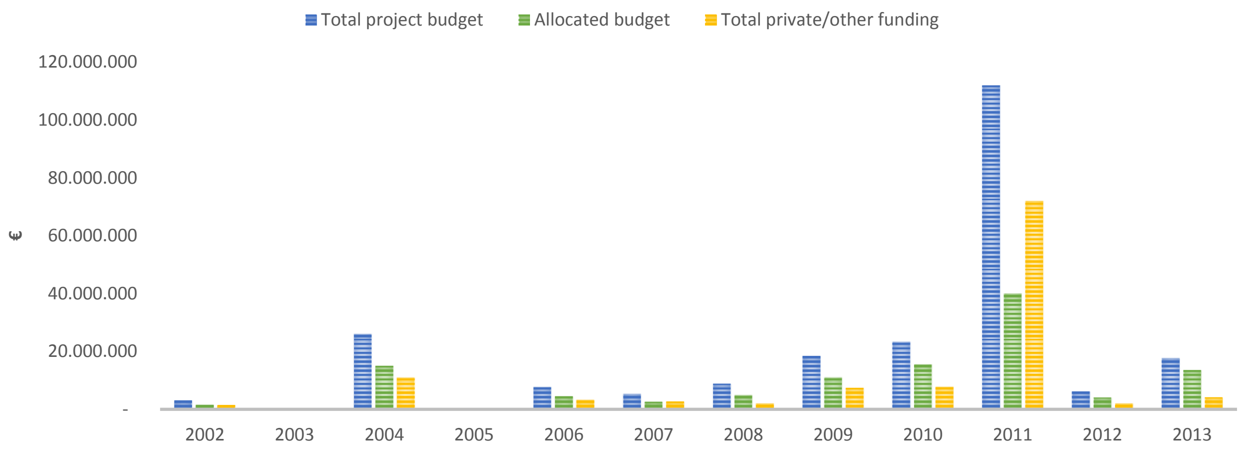

Figure 26. Budget allocated to Smart electricity grids theme from 2002-2013

3.2. Smart Electricity Transmission

Smart electricity transmission grids implement advanced technologies that can improve the security of supply and the network utilisation. These technologies can be phase-shifting transformers (PST) or flexible alternative current transmission systems (FACTS) and different half and full bridge technologies with and without direct current switching devices.

14 projects have been identified under this theme. It is visible from Figure 27 that the highest funding for the transmission theme was achieved in 2010, but it has been decreasing since that year.

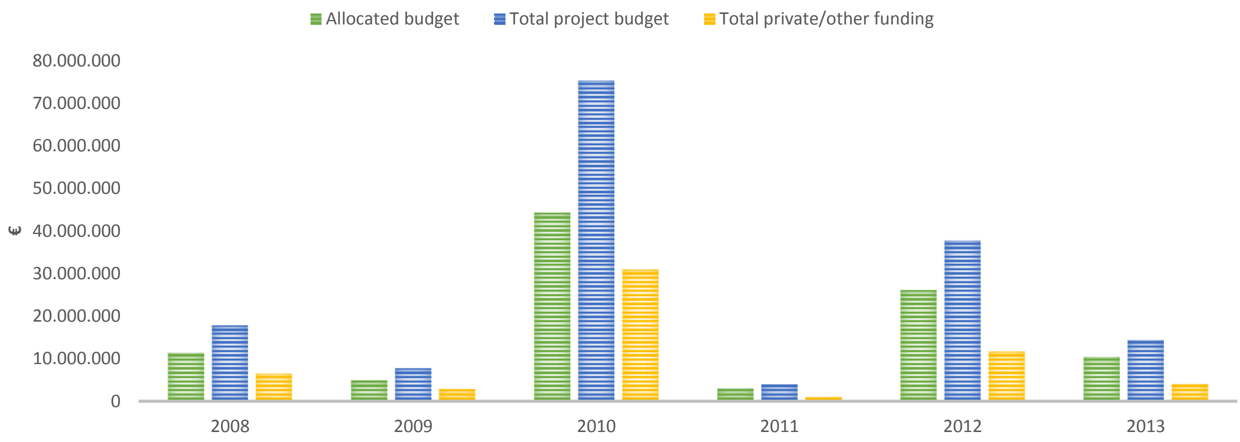

Figure 27.Budget allocated to Transmission theme from 2008-2013

3.3. Smart Electricity Distribution

Smart electricity distribution grids projects have an aim to match the demand with fluctuating supply, including different devices, software and services for real-time communication with users. Moreover, short-term storage capacity brings flexibility and supply-side management.

8 projects have been identified under this theme. As shown in *Figure 28*, the budget allocated to projects was highest in 2008 and was growing again in the period from 2011 to 2013 after two years of no funding. This could potentially be explained by the economic crisis.

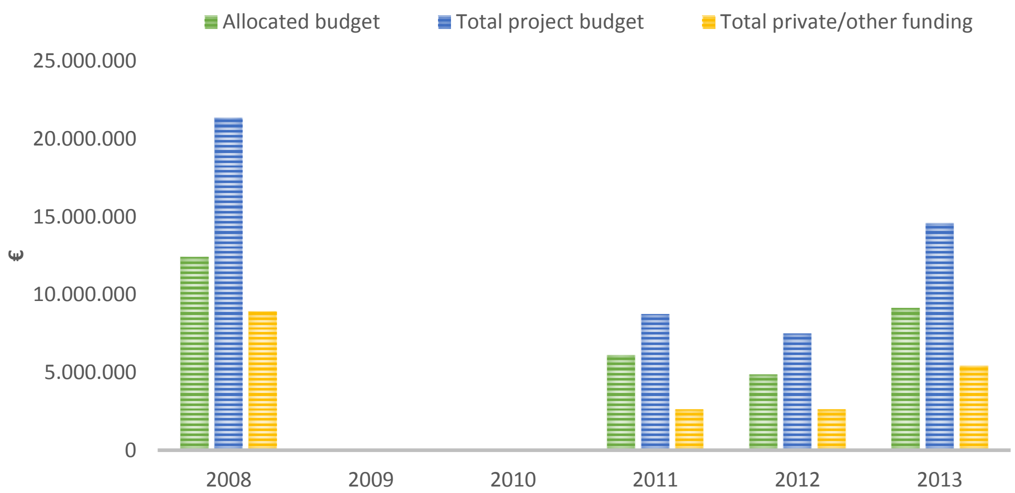

Figure 28. Budget allocated to Distribution theme from 2008-2013

3.4. Thermal grids / Cooling grids/ District heating and cooling (DHC)

The research theme of Smart district heating and cooling grids is divided into demand and supply side and it gathers projects involved with improving the management of energy demands and the supply side by use of heat storage and absorption refrigerators with appropriate control systems. This area is cross-cutting as it also includes integration with other types of networks. The theme is subdivided into: low-temperature district heating, district cooling, renewable energy sources, waste-to-energy and surplus heat in smart DHC, smart DHC as an integrated system, optimisation of existing infrastructure, and monitoring, forecast and costs studies for smart DHC development.

18 projects have been identified under the main theme of Smart DH and DC grids from both supply and demand side. Out of these 18 projects, 3 projects are identified as projects working with an integrated system: E-HUB, EcoHeat4Cities and FC-DISTRICT.

E-HUB (www.e-hub.org) - District Heating, Cooling & Power with on-site renewable energy: the project was running from 2010 to 2014 and had a focus on demonstrating the full potential of providing 100% renewable energy on-site within an "Energy Hub District".

EcoHeat4Cities (www.ecoheat4cities.eu): This project was running from 2010 to 2012 and it had an aim to support the acknowledgement, development and application of District Heating and Cooling systems. As a result, a visual label with heating or cooling performances of existing (and planned) district heating and cooling systems was developed. This labelling system is useful for policy makers, municipalities, urban planners, and citizens to gain knowledge of the energy and environmental performance of these types of systems.

FC-DISTRICT - New µ-CHP network technologies for energy efficient and sustainable districts (www.fc-district.eu): The project was running from 2010 to 2014 and it was supported by FP7 – NMP *New technologies for energy efficiency at district level*. The aim of the project was to exploit co-generation coupled with heat management in buildings and district heating network and heat storage.

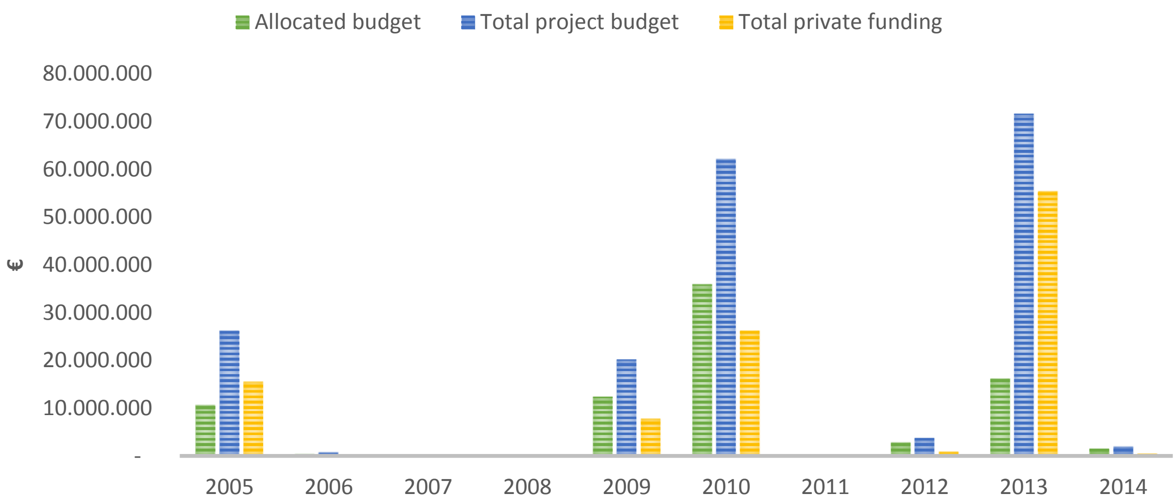

Figure 29. Budget allocated to smart district heating and cooling grids theme from 2005-2014

Figure 29 shows the budget allocated to the smart district heating and cooling grids theme. The first projects were funded in 2005 but there was no further funding until 2009. 2010 was the year with the largest amount of financing from the European Commission, but the largest project budgets were seen in 2013.

3.5. Storage

Under the storage theme, different types of storage technologies such as thermal, electrochemical, chemical, electrical or mechanical are included. In addition, the integration of storage technologies in energy systems is added as an important aspect of storage technologies. The 16 identified projects included electricity and heat storage at small, medium and large scales but most of the projects were focused on electricity. Out of 16 projects, 2 had the integration in energy systems as a focus:

stoRE - Facilitating energy storage to allow a high penetration of intermittent renewable energy (www.store-project.eu). This project was running from 2011 to 2014 and has contributed by creating regulatory and market conditions for energy storage infrastructure needed for the integration of renewable energy into the electricity grid.

eStorage - Solution for cost-effective integration of renewable intermittent generation with the demonstration of the feasibility of flexible large-scale energy storage with an innovative market and grid control approach (www.estorage-project.eu). This is an ongoing project started in 2012 with the objective to improve the integration of intermittent renewable energy into the electrical grid.

Figure 30 shows the budget allocated to energy storage projects. The first projects funded under this main theme were in 2008 and the highest funding was achieved in 2012.

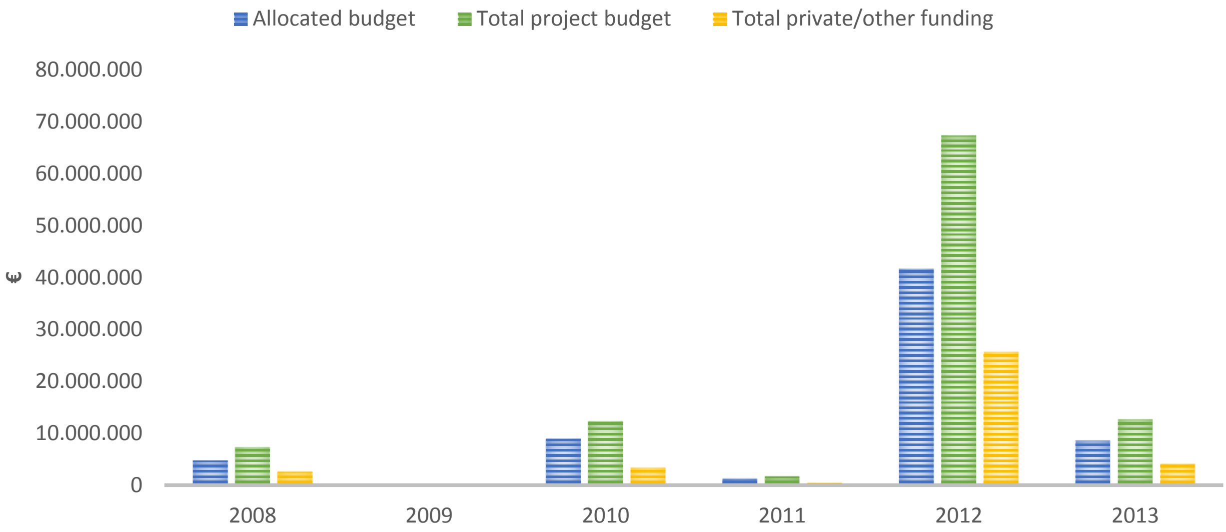

Figure 30. Budget allocated to storage theme from 2008-2013

3.6. Alternative transport fuels

Alternative transport fuels are of great importance in energy systems and they can reduce the dependency on a single energy source. Different chemical energy carriers such as synthetic fuels, LPG and different electricity applications for transport are part of the theme Other alternative transport fuels. Electricity as an energy carrier is divided into: drive train technologies, electricity storage systems, vehicle integration, and transport system integration. There are 64 projects under this theme and their distribution under the sub-themes can be found at [31]. A total funding of 403 MEUR is allocated to these projects. None of the projects has been identified as cross-cutting between electricity and liquid or gaseous fuels for transport, but there are 9 projects identified as relating to the integration of smart electric vehicles in the electricity grid.

Under the Alternative transport fuel priority area there are also projects on fuel cells and hydrogen. 37 projects are under the main theme of Fuel cells and hydrogen with a total funding of 225 MEUR.

3.7. Horizon 2020

As the list of projects granted by Horizon 2020 is not yet publicly available, this section presents the Work Programme for Horizon 2020 from 2014-2015. Overall, compared to previous programmes, the Horizon 2020 Work Programme shifts focus towards greater integration and interaction of energy sectors, but at a limited level. The calls are purposely designed to be open for interpretation, thus not precluding certain research areas. This is a very important element to the text.

Most calls that focus on the integration of the sectors are limited to the early stages of smart energy focus. The purpose of most of the calls at this stage is mainly to develop the precursors for the mass adoption of smart energy. For example, the call related to heat recovery in industrial processes (EE 18) is focused on increasing heat recovery and avoiding waste heat, but the call is open to how the heat may be utilised. The focus is on the precursor to utilising the heat, which is the recovery of heat first. The heat may be utilised by the industry providing heat to itself or feeding the heat into the heating grid as part of a smart system; this is decided by the applicant.

Most call texts have been written so that they are open for interpretation. As explained in the text: "*An important novelty of this work programme is its challenge-based approach which gives applicants more freedom to come up with innovative solutions to the outlined challenges. As a consequence, topics are generally broader and allow a range of possible approaches, often encompassing more than one possible action.*" This means that although some calls do not explicitly state that they focus on system integration, there is the option to submit an application about this.

In general, there are more calls written for Smart Grids focusing on electricity management. Focus is also placed on supergrid infrastructure for inter-country electricity trading. The LCE 06 call states: "*The integration of renewable energy and emergence of new services and uses of electricity will require major upgrades and reinforcements of the Pan-European power system. A realistic implementation of the "Smart Grids" concept across national borders becomes a requirement to continue the safe operation of the grid.*" This shows that full-scale integration of the electric grid into other sectors is still not a main focus in these calls.

However, at the building level in the call EE 6, which is focused on demand response in buildings, the focus is on thermal and electric energy management involving the users of the buildings. And this is open to smart energy applications. Smart metering is a main focus for thermal and electric grid management, for improving efficiency, and lowering costs.

Calls LCE 8, LCE 9 and LCE 10 focus on energy storage - from small-scale to large-scale and next generation technologies. Overall, these calls are focused on greater integration of energy sectors, for example with Power to Gas. Furthermore, there is the option that the application can investigate direct *or indirect* electricity storage. In general, the next generation storage is open to interpretation and applications can involve different solutions that do not only look at electric storage.

In terms of transport fuels, the focus is on new biofuels and advanced biofuels, and although no mention is made about finding synergies with other energy sectors to produce the fuels, for example using excess electricity to produce electrofuels, the call is open to interpretation and solutions. It is explicitly stated that next generation biofuels should exclude fuels from starch, sugar and oil fractions of food/feed crops.

Smart gas grids are also considered in call LCE 14 which focuses on biogas/biomethane from manure and other waste and the integration into the gas grid.

There are not many calls related to fossil fuels which is in line with the Smart Energy concept. However, there is some focus on shale gas exploration and reducing its impacts. This is not related to smart energy systems. Another example is developing highly efficient fossil fuel power plants that will deliver peak demand in the electricity sector when renewable electricity has a high penetration.

In terms of concrete smart energy projects, the first steps are taken in the Smart Cities and Communities call SCC 1. This call aims to demonstrate solutions for integrating energy, transport, and ICT sectors in lighthouse projects. These calls show the first signs of specific projects focusing on system integration and smart energy development on the ground.

Overall, a step forward has been made with the Horizon 2020 calls where a more integrated approach is supported.

3.8. Summary of project funds

Figure 31 shows the share of the main themes presented out of the total funds for specific main themes under the 9 priority areas. It is visible that the themes related to the smart electricity grid (including transmission and distribution) have a total of 6% of funding. The only theme with a higher share than this is the other alternative fuels theme. Smart district heating and cooling grids have only 2% of the total budget.

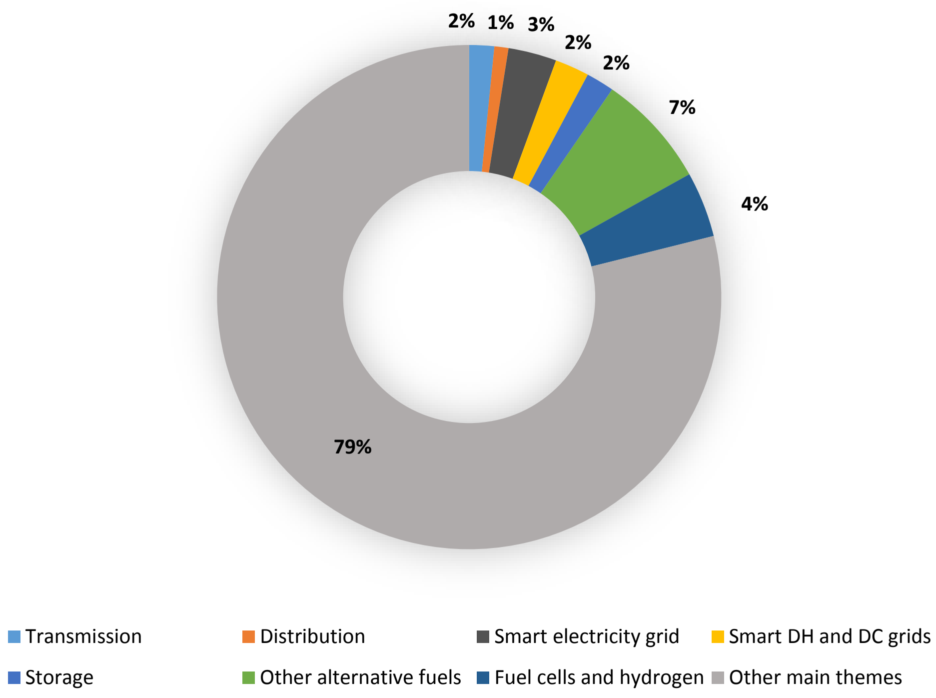

Figure 31. Share of main theme project budget under the total EU budget

Figure 32 shows the distribution of funding under the previously presented themes (excluding transport) and the number of projects that was included. It is visible that the focus of the projects was on smart electricity grids (including distribution and transmission) with funding of ~440 MEUR and 49 projects in comparison to ~185 MEUR for smart district heating and cooling projects. Energy storage projects also include the electricity storage theme with a high share of 16 projects.

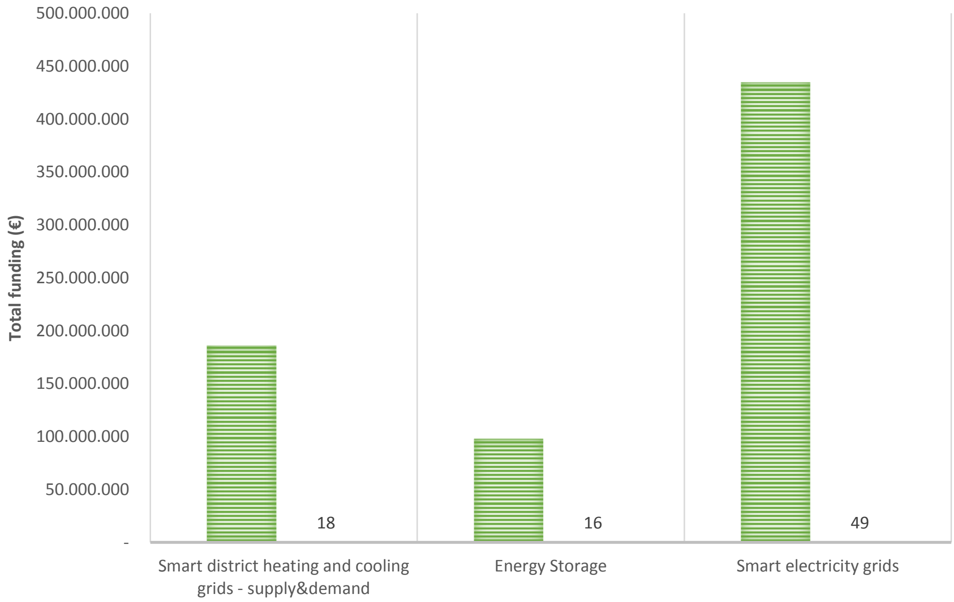

Figure 32. Total funding and project number under different themes

The funding shares for all these themes are visible in Figure 33, showing that 60% of the total funding was allocated to smart electricity systems and grids. This is a significant share in comparison to 26% for thermal and cooling grids. Energy storage with 14% combines different types of storage including thermal and electricity.

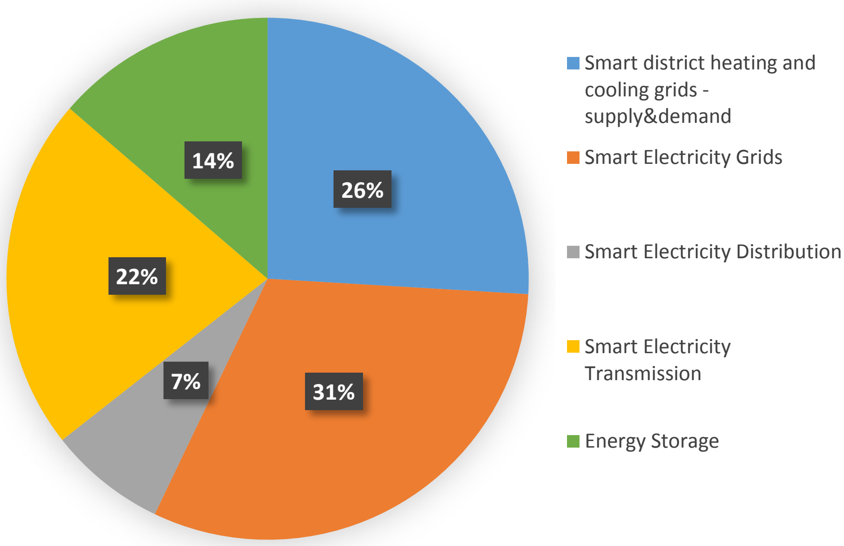

Figure 33. Share of EU project funding according to different themes

Figure 34 shows combined funding in smart electricity grids, in the transmission and distribution theme from 2002 to 2013. It is visible that the funding peak happened in 2011 and funding was reduced in the following years. The storage projects did not have a high share of funding and most of the projects were funded in the period from 2010 to 2012.

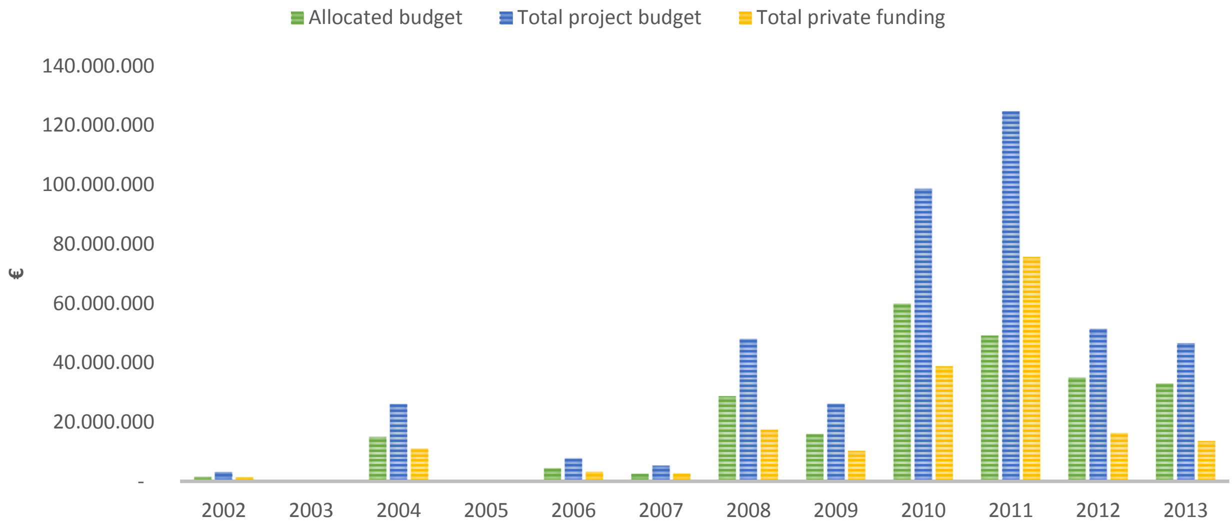

Figure 34. Funding in Smart electricity grid, Transmission and Distribution theme in the period from 2002 to 2013

It is visible from the amount of funding allocated to certain themes that the focus within Smart Grids is still given to the *smart electricity grids* and this research area is growing rapidly. Many individual technologies have been developed during the last 15 years, but there is still a need for further market and service levels and the integration of electricity grids with other supply grids.

The *smart district heating and cooling* activities have mostly focused on the development of the technology, the renewable energy integration within these grids, the connection with thermal storage, heating and cooling demand mapping, and cost optimisation. There have been few activities on the European level on the interaction with other supply grids, but this research needs to be targeted further in the new EU funding calls and political activities.

Energy storage technologies are of high importance in the integrated energy systems and can offer flexibility to the system. Previous research efforts on the European level have been focusing on different types of energy storage but mostly on the efficiency and costs related issues. Further focus on the new storage technologies, their demonstration and cross-cutting storage research is necessary to achieve further efficiency improvements on the system level.

Clearly the electrification of transport is prioritized in the previous activities, which is without doubt the right way to continue; however, as some of the transport modes are not suitable for electrification such as heavy-duty or aviation, there is a need for more focus on funding opportunities for projects that can offer a solution for these parts of the transport sector and have more cross-sectorial integration.

Part B: Smart Energy state-of-the-art

1. Introduction

The purpose of Part B is to present the Smart Energy state-of-the-art research. To create a comprehensive overview, state-of-the-art research was gathered from a wide range of experts. Based on the expert input, numerous research areas have been described for the technical and non-technical aspects of Smart Energy and these include:

- Electricity grids, infrastructures and technologies
- Thermal grids, infrastructures and technologies
- Gas grids, infrastructures and technologies
- Cross-cutting interaction between the three energy sectors
- Social, socio-economic and political dimension

Parts of the transport sector and the consuming and producing units have also been described. For example, the demand side of Smart Energy in housing, industry, etc.

The results from the review are presented below but firstly the state-of-the-art definition of Smart Energy is described.

2. State of the art definition Smart Energy Systems

The state-of-the-art definition of Smart Energy is presented here with the aim to clarify what Smart Energy encompasses. Smart Energy arises as a solution to the fact that the future energy system will rely on renewable energy resources such as wind and solar power. These resources do not contain large amounts of stored energy, but instead the energy from the wind, sun, waves and tides must be captured and used immediately. This is one of the key technological challenges facing energy systems in the future. The question is: Based on renewable energy how can the future energy system operate without the flexibility currently being provided by large amounts of stored energy in fossil fuels? While simultaneously providing affordable energy and utilising a sustainable level of the resources available. The solution will be to find new forms of flexibility within the energy system which are affordable and utilise renewable energy resources in an efficient manner. This is called a smart energy system or Smart Energy.

In recent years, a number of new terms and definitions of sub-energy systems and infrastructures have been promoted to define and describe new paradigms in the design of future energy systems such as Smart Grid [32], 4th generation district heating [33],Vehicle-2-Grid [34] and power to gas [35]. All these infrastructures are essential new contributions and represent an important shift in paradigm in the design of future renewable energy strategies. However, they are also all sub-systems and sub-infrastructures which cannot be fully understood or analysed if not properly placed in the context of the overall energy system. Moreover, they are not always well defined and/or are defined differently by different institutions.

The issue of sub-systems versus overall energy systems is carefully analysed in [36] and [37] and are here referred to as the concept of smart energy systems. As opposed to, for instance, the Smart Grid concept, which takes a sole focus on the electricity sector, smart energy systems include the entire energy system in its approach to identifying suitable energy infrastructure designs and operation strategies. One main point is that in order to do a proper analysis of any Smart Grid infrastructure, one has to define the overall energy system in which the infrastructure should operate. Another main point is that different sub-sectors influence one another and one has to take such an influence into consideration if the best solutions are to be identified.

A smart energy system consists of new technologies and infrastructures which create new forms of flexibility, primarily in the 'conversion' stage of the energy system. This is achieved by transforming from a simple linear approach in today's energy systems (i.e., fuel to conversion to end-use), to a more interconnected approach. In simple terms, this means combining the electricity, thermal, and transport sectors so that the flexibility across these different areas can compensate for the lack of flexibility from renewable resources such as wind and solar. The smart energy system is defined in [38] and is illustrated in Figure 35 and Figure 36 and uses technologies such as:

Smart Electricity Grids to connect flexible electricity demands such as heat pumps and electric vehicles to the intermittent renewable resources such as wind and solar power.

Smart Thermal Grids (District Heating and Cooling) to connect the electricity and heating sectors. This enables the utilisation of thermal storage for creating additional flexibility and the recycling of heat losses in the energy system.

Smart Gas Grids to connect the electricity, heating, and transport sectors. This enables gas storage to be utilised for creating additional flexibility. If the gas is refined to a liquid fuel, then liquid fuel storages can also be utilised.

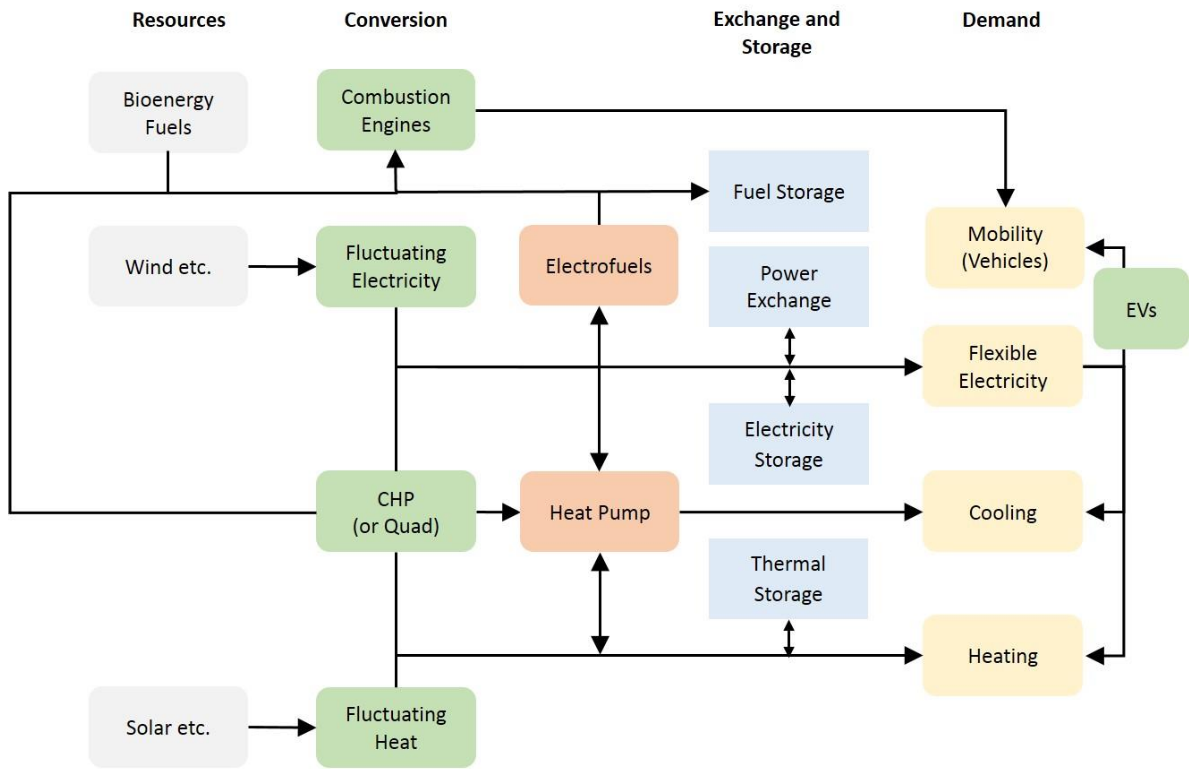

Figure 35: Smart energy system flow diagram [2,39,40]

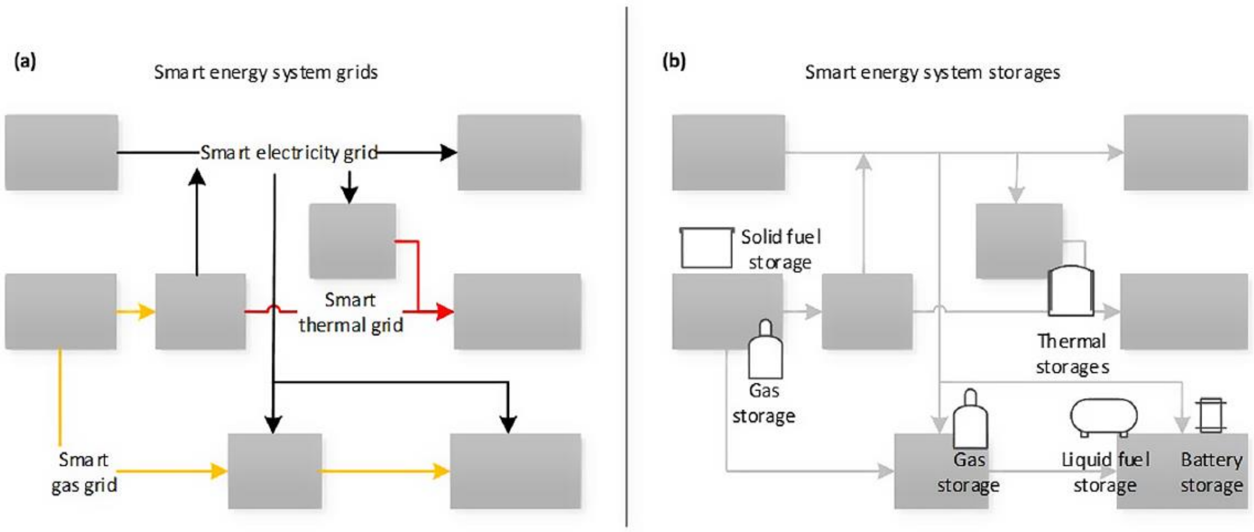

Figure 36: Energy-flow-diagrams of the grids (a) and storages (b) in Smart Energy Systems[38]

In Figure 36 grids and storages in Smart Energy Systems are illustrated. By combining the electricity, thermal, and transport sectors, the grids and storages in these sectors can improve the energy system flexibility and compensate for the lack of flexibility from renewable resources such as wind and solar. In the three grids, the storage and connections between sectors is comprised of smart electricity grids, smart thermal grids and smart gas grids.

Smart electricity grids are electricity infrastructures that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.

Smart thermal grids are networks of pipes connecting the buildings in a neighbourhood, town centre or whole city, so that they can be served from centralised plants as well as from a number of distributed heating or cooling production units, including individual contributions from the connected buildings. _

Smart gas grids are gas infrastructures that can intelligently integrate the actions of all users connected to it – suppliers, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure gas supplies and storage.

Based on these fundamental infrastructures, a Smart Energy System is a design in which smart Electricity, Thermal and Gas Grids are combined and coordinated to exploit synergies to achieve an optimal solution for each individual sector as well as for the overall energy system. Short and long term storage options, such as batteries and large thermal storages, as well as solid, gaseous and liquid storages are key components in 100% renewable energy systems and so are the infrastructures and grids that enable such storage.

The smart energy system concept described above was the first definition of Smart Energy on a system level encompassing all energy sectors. Other definitions of Smart Energy exist today; however, there is less research done on a system level for these definitions than has been done for the concept defined here. The definition of Smart Energy defined here should not be seen as an isolated research area but it is broad and encompasses a wide range of technological solutions and research areas which are described below.

3. Electricity grids, infrastructures and technologies

In this section, the state-of-the-art research for the electricity sector in Smart Energy is described. Table 6 below presents a brief overview of the main topics in the state-of-the-art research. The main research gaps are also presented in Table 6. Although some areas are currently being researched, research gaps may also occur in the area; thus, they are included in both columns in the table.

Table 6: Summary of key areas included in state-of-the-art Smart electricity research, and research gaps

State-of-the-art topics	Main research gaps
Electricity infrastructures – Smart Grid management	Electricity grid in the future energy system
ICT, meters, communication, algorithms	ICT, meters, communication, algorithms (Advanced monitoring)
Electricity/energy storage	Electricity/energy storage
Demand side response, DSM, flexible demand	

A detailed description of the state-of-the-art research in the electricity sector is presented below, beginning with a summary.

Summary of the state-of-the-art

The electricity grid can contribute to smart energy systems by ensuring a reliable and efficient grid operation with increasing shares of intermittent electricity from renewable energy generation technologies and by contributing to balancing supply and demand. Recent advances in energy systems have contributed considerably to the reliability and integration of intermittent energy from renewables. For example, building integrated photovoltaics (BIPV) have greatly reduced the initial cost on infrastructures. The power electronics interfaced variable speed wind generators, such as doubly-fed induction generators (DFIG) and permanent magnet synchronous generator (PMSG), provide the system operator with enhanced controllability and reliability [41]. Meanwhile, the remote located offshore wind farms can be integrated with onshore power systems with high voltage dc (HVDC) links. Concerning the balancing of supply and demand, energy storage systems, such as compressed air, batteries, superconducting magnetics, etc., have been developed as another enabling technology to buffer the surplus renewable power generations.

Despite the enormous efforts devoted, there are still remaining challenges to accommodate more and more renewable power. For instance, the temporal and spatial correlation of renewable power generations is likely to cause network congestions and energy curtailment. Thousands of miles of energy transmission to the load centres suffer from huge network investments and large losses. Inaccurate predictions lead to considerable mismatch between the offline simulation and the real time patterns, and electricity prices are always being volatile with unpredictable variations due to the changes of the generations, etc. More focus should be placed on intelligently integrated energy systems and consequently on virtual storage solutions.

Storage technologies represent an area in need of further research, but primarily where they relate to transport (e.g., lithium batteries). Other areas for further research are related to integrating the electricity grid into the rest of the energy system and in advanced monitoring.

3.1. Conventional network expansion versus Smart Grid (Electricity infrastructures)

In an intelligent integrated electricity system – a Smart Grid – completely new perspectives will emerge. The consumers will be able to interact with the power system and generation through automated and intelligent control of their electrical appliances, thereby acting as resources for the power system. Reinforcing the transmission network in this way can remove the bottlenecks and congestions. In most EU countries, the natural gas systems and power transmission systems are operated by the same enterprises like Energinet.dk. As a result, coordinative expansion planning is needed, not only in the power system but also in the communication system, natural gas system, etc.

In terms of the social net cost of having a Smart Grid in Denmark, according to a recent report by Energinet.dk, the overall calculations show that a future power system using Smart Grid in Denmark can be established at a social net cost (present value) in the range of DKK 1.6 billion. However, this requires social investments of around DKK 9.8 billion. Hence the economic benefit of choosing the Smart Grid strategy is needed for lower electricity generation costs, a more effective production of ancillary services and increased electricity savings.

3.2. Households in the smart energy system (Demand side response, DSM, flexible demand)

In relation to residential electricity consumption, many trials and demonstration projects have been carried out within the last ten years. Focus has in particular been on *demand-side management* (or "demand response"), i.e. enrolling households as a resource for balancing the grid, and *feedback to household customers* about their hourly-measured electricity consumption with the aim of promoting energy savings. The latter is often provided by DSOs who offer their private customers an online feedback service (typically via a website or a smartphone app).

Overall, these trials and demonstrations have until now achieved limited results with regard to demand-side management (DSM) and energy savings through feedback. On a general level, a specific challenge with involving households in the smart energy system is that they represent a large and diverse group of customers with low individual energy consumption. Among other reasons, this makes it difficult to develop economically feasible schemes and services targeted at households.

In response to the system challenge of balancing demand and supply in an electricity grid increasingly based on intermittent renewable energy sources, a great number of projects have tested solutions for DSM in households. Also, peak-shaving has been in focus for several of these projects. A 2012 review identified 12 recent or ongoing Danish projects related to DSM in households (Christensen et al., 2013). These projects focused in particular on electric heating (direct and heat pumps) and EV charging, although some projects also addressed a broader array of residential electricity consumption (typically dishwashing and laundering). Also within the latest 3-4 years, several projects have addressed DSM in households, including:

- EcoGrid EU (2011-15): Large-scale trial of manual and automatic control of electric heating in households via aggregator (regulating power, 5-minutes price signals),
- iPower (2011-16): Addressing various solutions for DSM in households, including both automated control and communication
- FlexPower 2010-13: Testing DSM of automated control of electric heating in homes via aggregator (regulating power, 5-minute price signals).

- Dynamic Net Tariff (2012): Testing a static time-of-use scheme for the net tariff (including households with an EV).

These, and previous, projects tend to show the most promising results for solutions based on automated, remote control of household appliances (typically heating), whereas trials based on “manual” control by the household members based on price information show little effect. However, an exception seems to be the Dynamic Net Tariff trial that realized some peak shaving in residential electricity consumption through the participating households’ active involvement in time shifting a variety of their consumption (in particular dishwashing, laundering and EV charging). This was most likely due to the static time-of-use price scheme applied in this project, which was easier to understand and follow for the participants compared with dynamic real-pricing schemes based on 1 hour or even 5-minute intervals, which are used in most other trials [42]. This indicates that even DSM based on automated/remote control appears most promising as regulating power, and static time-of-use schemes might have a potential for more general time shifting of household load profiles.

As indicated, the DSM trials tend to fall into two groups: One that gives precedence to DSM based on automated, remote control of appliances. Usually, these projects imply an understanding of consumers not being interested in managing their energy consumption actively themselves. Users are represented as comfort and convenience seeking people who prefer to delegate the management of their energy consumption to automated systems. The second group of projects aims to motivate consumers actively in the management of their own energy consumption through information and price signals. These projects are typically based on a belief in the consumer as a price-sensitive and “rational” agent who, on the basis of economic incentives or other preferences (like environmental preferences), adapt his/her behaviour in order to save money and optimize utility [43–45].

Feedback

Along with the gradual roll-out of smart meters in Denmark, many DSOs and electricity suppliers offer their customers feedback about their energy consumption through websites or mobile phone apps. The feedback typically consists of graphs or tables showing the household’s hourly, daily or monthly electricity consumption. Some feedback solutions also offer the households the possibility of comparing the size of their own electricity consumption with other similar households. Examples of DSOs offering their customers feedback are SEAS-NVE, SE, EnergiMidt and Energi Fyn.

Only little documentation exists on whether the Danish feedback services result in electricity savings. Previous Danish and international trials indicate a limited potential, e.g. [46,47]. International research shows that the most successful feedback solutions should present energy consumption data in (close to) real-time and be based on non-aggregated consumption data (i.e., present an appliance-specific breakdown of the households’ electricity consumption) [48,49]. As the Danish feedback solutions in general do not satisfy these requirements (e.g., consumption data are often presented with a delay of one or more days due to technical reasons), it is not likely that they contribute to significant energy savings.

3.3. Advanced monitoring and control strategies in power systems (ICT, meters, communication, algorithms)

With the increasing system scale and complexity, the wide area damping controllers (WADCs) enable power engineers to access remote signals via the wide area measurement systems (WAMS) and phasor measurement units (PMUs). The signal processing time from PMUs to control centre has been abbreviated from minutes to milliseconds, which puts the fast dynamic monitoring and control of the system into practices. Meanwhile, the problem of optimal placement of PMUs has been raised. Due to the complexity and nonlinearity of the optimization problem, heuristic methodologies are used. In [50], an improved method of binary particle swarm optimization (PSO) technique has been introduced to solve the optimal placement of PMUs for complete system observability. Later work [51] takes some practical issues into consideration.

Since the control centre receives more data with much smaller time intervals, the system operators need a better visualization of the data to help justify the stability of the system running. In [52], a new three dimensional security index has been proposed for online security monitoring of a modern power system with large-scale renewable energy. The proposed security index combines the voltage, overload and reserve indices and can provide system operators with intuitive status.

Other mathematical tools have also been used in power system monitoring. Data mining techniques, involving methods of artificial intelligence, machine learning and statistics, and time series analysis are computational processes of discovering the useful information of data patterns from large data sets. Among many data mining techniques, especially those with “white box” nature, such as artificial neural network and support vector machine, a decision tree (DT) algorithm has gained increasing interest because it not only provides the insight information of data sets with low computational burden, but also reveals the principles learnt by DTs for further interpretation [53,54]. There is also a need for “grey-box” modelling. In [54], the systematic approach for dynamic security assessment has been proposed and applied to the Danish 2030 power system. Reactive power and voltage stability are also important with the transformation from the overhead to underground transmission system in Denmark. According to the guidelines, new 132 - 150 kV power lines will be installed as underground cables, and the existing 132 - 150 kV overhead lines will be undergrounded by 2040 [55].

3.4. Energy storage solutions (Electricity/Energy storage)

Although the active power regulation is demonstrated to be essential in modern power systems, the main present challenges to the application of energy storage in the power system are to bring down the cost, as the price per MVA for energy storage is much higher than other FACTs and increases exponentially with its capacity. With advanced control strategy, the energy storage devices can be used more efficiently[56].

In Denmark, the main purposes of using energy storage are listed as follows:

- Adding flexibility to the electricity and heating system.
- Facilitating the substitution of fossil fuel by renewable energy.
- Minimizing the cost of renewable generations.

Norway, as one of Denmark’s neighbouring countries, has a special capability to balance Denmark's fluctuating power generation. Norway’s electricity demand is fully supplied by renewable hydropower, which can be controlled in the sense that the water flow can be stopped and water can be stored in huge (currently 20) reservoirs able to hold about 85TWh. This capacity can even be expanded and Centre for Environmental Design of Renewable Energy (CEDREN) estimates that in 2030, a potential Norwegian power storage capacity of 20 GW could be possible. At the moment, Denmark is the main customer for these services, but the future interconnections between Norway and the Netherlands, as well as Germany and the UK, will intensify the competition for the Norwegian storage services and thus this opportunity may well become less attractive in the future than it is right now. Furthermore, the Norwegian hydropower production is somewhat dependent on annual rainfall in Scandinavia (as reflected by NordPool electricity prices) and thus Norwegian hydropower may in some years not be completely stable.

Denmark is also developing energy storage at the system level to increase the grid flexibility. The power-to-gas (P2G) technology represents a megawatt-level energy storage solution to the problem of surplus energy from renewables, as shown in Figure 37. At *Renseanlæg Avedøre*, Electrochaea is now building a 1 MW electrolysis plant, where electricity from wind power and water is converted into hydrogen [57]. Hydrogen is used for upgrading biogas before it is injected into the natural gas grid.

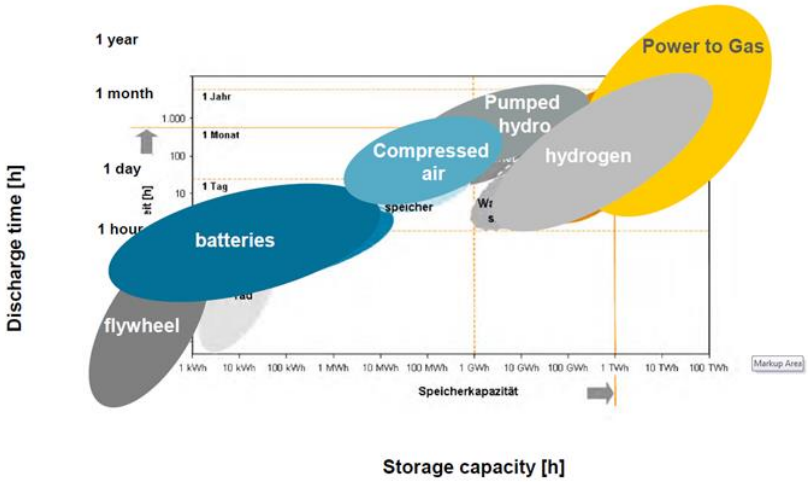

Figure 37: Energy storage technologies review (source: [58]*)*

3.5. Active distribution systems (Demand side response, DSM, flexible demand)

Modern distribution systems have been equipped with more and more power electronics interfaced dispersal generations, which makes the distribution systems more controllable[59]. Other intelligent devices like smart transformers, energy storage systems, smart loads, etc., can also be used to improve the overall efficiency of energy distribution. The concept of droop control at transmission level can be embedded in the control strategies of the above-mentioned energy conversion systems. An adaptive droop control method is proposed based on an online evaluation of the power decouple matrix for inverter connected distributed generations [60].

From 2005 to 2011, Energinet.dk, cooperating with a series of enterprises, 47 wind turbine owners and 5 local combined heat and power (CHP) plants, has conducted the Cell Controller Pilot Project (CCPP) towards the future intelligent power system. In this project, a hierarchical control strategy is implemented from the control centre of the transmission system to the asset owners at the distribution level. The trade-off between the centralized and agent-base (decentralized) control is optimized by carefully defining the control functions at each level. The principal Danish partners in the CCPP are currently working on setting up a full utility scale Smart Grid test facility utilizing the existing Cell Controller installation in the Holsted cell area. This "Test Centre Holsted" is expected to be open to all interested parties like Smart Grid related industries, research institutes and universities on commercial terms.

3.6. Further research

Electricity grid in the future energy system

The future electricity grid should be seen as an integral part of the other energy sectors such as gas (power to gas), thermal (electricity to heat) and transport (EVs). Renewable energy will need to be stored as energy in some form and the integration of the electricity grid into these sectors will provide storage capacity and increase the system flexibility. The research gap lies in the fact that the grid is not researched as an integral part of the other energy sectors at present. Once it becomes researched in this way, options to store fluctuating renewable electricity will be made available and the overall system will become more flexible.

In addition, once the electricity grid is seen as integrated in the rest of the energy system, virtual storage solutions can be harnessed. This is where supply of the electricity does not meet demand, but rather demand meets supply, and one large potential for virtual storage is in the building stock and industry. It is also evident when combining and interacting the electricity and the gas sectors.

Advanced monitoring and control strategies in power systems (ICT, meters, communication, algorithms)

The research in the SOSPO project [61] focuses on methods that enable system stability and security assessment in real-time and on methods for automatically determining control actions that regain system security when an insecure operation has been detected. Traditional approaches to determining the stability and the security of a given operating point are based on a time consuming offline analysis. In a system where power is mainly produced by means of uncontrollable renewable energy sources, the increased fluctuations of the system's operating point will make the planning of stable and secure operation a challenging task. In fact, it means that operational planning can no longer be carried out several hours ahead, since the conventional means for planning secure operation will not be adequate.

For the future sustainable power system, there is a need for methods that can provide a stability and security assessment (SSA) of the instantaneous operating conditions in real time.

Electricity/Energy storage

The goal of an energy system with a high penetration of renewable energy production will be difficult to obtain in Denmark without Energy Storage Solutions (ESSs) located on all grid levels. Currently, on the transmission level, the exchange of power with neighbouring countries acts as a storage system by importing power (discharging) during low wind conditions and exporting power (charging) when wind power plants have an overproduction. Nevertheless, similar approaches are needed on the distribution level and on the low voltage grid level, especially when a higher number of prosumers and EVs are expected in the near future.

There exist a number of challenges that need to be addressed for rechargeable batteries to become more useful in clean energy applications. The most important challenge is cost; significant development is required to reduce cell prices. Other challenges include energy density (volumetric and gravimetric), lifetime, and environment impact.

Recent advances within battery technology have opened new possibilities for the application of high power and high energy lithium-ion batteries. Lithium-ion (Li-ion) batteries have become the standard choice for the e-mobility (e.g., plug-in hybrid electric vehicles, fully electric vehicles, etc.) and consumer applications (laptops, tablets etc.) because of their outstanding characteristics, which include high gravimetric and volumetric energy density, high operating voltage level, and long calendar and cycle lifetime [62].

Li-ion batteries are becoming attractive for short- and medium-time (i.e., minutes to one hour) stationary energy storage applications [62,63] but are still constrained by their cost competitiveness [64]. A solution to minimize this issue is to use the Li-ion batteries in a proper and efficient way, i.e., by avoiding operation regimes which can cause fast degradation and inefficient use of the battery. This can be realized by having accurate information about the battery's lifetime and its performance-degradation behaviour, which is caused by ageing. In addition to an improved understanding of cell level performance, research into complete packs and systems is important to further mature the technology.

There is substantial materials chemistry research being conducted into lower cost, safer, higher energy density electrodes and electrolytes. A recent development is carbon-carbon battery [65], which promises higher energy density and lower environmental impact than standard li-ion cells. The lithium-air battery and lithium-sulphur battery [66] both promise significant improvements, but at present do not exhibit the cycle life for full commercialisation.

The battery management system and the thermal management system are areas that need further research and development to improve the overall efficiency and lifetime of the system in real application.

4. Thermal grids, infrastructures and technologies

In this section, the state-of-the-art research for the thermal sector in Smart Energy is described. Table 7 below presents a brief overview of the main topics in the state-of-the-art research. The main research gaps are also presented in Table 7. Although some areas are currently being researched, research gaps may occur in the areas; thus, they are included in both columns in the table.

Table 7: Summary of key areas included in state-of-the-art Smart thermal research, and research gaps

State-of-the-art topics	Main research gaps
Improved district heating and cooling	Energy efficiency in thermal system (Zero Emission Buildings, Intelligent control of heating)
Energy efficiency in thermal system	New heat infrastructures and systems (Reversible heat pumps)
New heat infrastructures and systems (Reversible heat pumps)	ICT, meters, advanced monitoring
Models	Improved district heating and cooling (improved district heat pipe insulation, smaller pipe dimensions)
Waste heat from industry	

A detailed description of the state-of-the-art research in the thermal sector is presented below, beginning with a summary.

Summary of the state-of-the-art

An advantage of the thermal grid is that provides a storage solution of energy. The thermal grid can contribute to the Smart Grid by offering energy storage for surplus electricity (conversion by means of heat pumps) and by providing improved energy efficiency by allowing the utilisation of otherwise discarded heat, for example when using CHP for electricity production. Recent advances in, e.g., heat atlases have improved the planning basis in relation to low-temperature district heating systems. Such advances in the planning basis have been complimented by research into how low-temperature district heating may interact with energy renovations of the existing building stock or new buildings. Another line of research has investigated how domestic heat pumps and storage tanks may be integrated into overall Smart Grid strategies. Further research is needed to optimise the interaction between the smart thermal grid and the housing stock.

One important advantage of district heating systems is the possibility to provide improved energy efficiency which contributes positively towards energy security. The EU has promoted district heating and combined heat and power (CHP) as energy efficiency measures through the Energy Efficiency Directive (Directive 2012/27/EU) [67].

A transition of energy systems is occurring worldwide, which includes efforts to improve energy efficiency and increase the integration of variable renewable energy sources (RES) in the electricity system (e.g. large-scale heat pumps). On the one hand, the increased production from variable RES results in reduced electricity production by CHP units, thereby reducing their feasibility. On the other hand, society relies on CHP capacity to efficiently produce electricity when variable RES does not. Consequently, it is essential for society that a CHP capacity is maintained in the system and that it can be achieved through market set-ups, especially with respect to the EU goals.

4.1. CHP and electricity markets (Improved district heating and cooling)

The simulation of CHP plants is well described in literature [68]. The challenges in the daily operation have not received much attention; however, some studies have investigated strategies for the daily electricity trading of DH plants. Pirouti et al. [69] describe a method for the optimal daily operation of a biomass CHP plant with a thermal storage unit trading electricity on a day-ahead wholesale market. Rolfsman [70] describes an optimization model for the daily operation strategy of CHP plants utilizing thermal storage units on a day-ahead wholesale market and an intra-day wholesale market. The model uses a simplified approach to the prices on the intra-day wholesale market. For the wholesale market, a price forecast is used for the coming 24 hours. Thorin et al. [71] introduce a model for the optimization of CHP plants operating on both a day-ahead wholesale electricity market and a frequency restoration reserve market. Andersen and Lund [72] calculate the activation bids on a balancing market by using forecasts of heat demand and wholesale market prices. Sorknæs et al. [73] discuss the operational challenges for a small district heating plant that is participating in the electricity system balancing in an energy system with a high share of variable RES. Sorknæs et al. [74] investigate the potential for small CHP plants to participate in the balancing of the German electricity system through the market-based balance regime.

In recent years, there has been a strong focus on mapping of heat demands in the form of heat atlases. Heat atlases are used on different levels from municipal [75,76], regional [77] and national [78] to European [79]. The Danish Heat Atlas [80] has been under development since 2008 and has recently been updated based on measured data from individual buildings. Heat atlases have been used for district heating expansion planning [81–83].

Recent studies [33,84] have an emphasis on the role of district heating systems in the future sustainable energy systems; however, converting to a low-temperature district heating network is an essential need in order to interact with low-energy buildings and integrate district heating into smart energy systems. [33] elaborates the main challenges to be fulfilled by low-temperature DHS as following: supplying heat to existing buildings, low-energy and energy-renovated building through low-temperature DH; reducing the thermal losses in pipe networks; utilizing heat from low-grade heat sources, integrating DH with the smart energy system, and prediction-based controllers based on online data.

4.2. Thermal-dynamic modelling tool (Models)

In Madsen et al. [85] from 1992, models and methods for the optimisation of district heating systems are described. These models and methods have been used to derive new methods for model-based control of the temperature levels in district heating systems in [86] and [87] from 1996 and 2002. These methods were implemented in TERMIS TO, using a simulation based control approach, and, for prediction-based control, using available online data from the thermal network in PRESS [88]. The overall set-up of the intelligent control is described in [89] and [90]. Using the simulation-based approaches, like those implemented in TERMIS TO, leads to up to 10% savings of the thermal loss in the district heating network, while the data and prediction-based control approaches lead to up to 20% savings of the thermal loss. More facts are provided in [90].

With the aim to lower the temperature gradient and heat losses through the distribution grid, a thermal-dynamic modelling tool has been developed in MATLAB. The model assesses the DHN operational performance under alternative options including supply temperature, pipe types, network length and heat loads in the network. A comprehensive model to evaluate the dynamic heat transfer in a DHN has been developed. The model can ultimately be used for techno-economic assessments of different development options for an existing DHN. The heat sources are connected to the consumers through pipe networks. The dynamics of pipe networks, which are mainly due to the time delays and heat losses through the distribution networks, are reflected in the model. The tool is applied to short-term or long-term simulations of DHN operation. The developed model is used to study stepwise changes in existing district heating networks moving towards low-temperature district heating.

Initially, the developed tool was applied to model a DHN in Studstrup, Denmark, where the heat is distributed to 321 consumers through 13 km pipelines. The modelling was based on the network's hourly operational data and the derived results were validated against TERMIS and real-life measurements. Next, a techno-economic assessment was performed by replacing the pipe networks by pipes with improved insulations series and lowering the temperature level in the networks. The network heat losses and life-cycle cost were used as performance indicators to compare the alternatives.

Models for prediction based temperature control for low temperature district heating systems has been developed. The principles show leading temperature savings when implemented in online systems like PRESS.

4.3. Energy and heat savings (Energy efficiency in thermal system)

The design and perspective of new low-energy buildings have been analysed and described in recent papers [91,92], including concepts like energy efficient buildings [93,94], zero emission buildings, and plus energy houses [95–97]. Some papers address the reduction of heat demands in existing buildings and conclude that such an effort involves a significant investment cost [98].

Consequently, an important question is to which extent these heat savings can be implemented in a future smart energy system with a significant share of district heating. [99] Furthermore, smart energy systems combine and coordinate smart electricity, thermal and gas grids to identify synergies between them and to achieve an optimal solution for each individual sector as well as for the overall energy system. This relates to savings as well. Possibly better performances of energy savings can be found by combining and connecting different parts of the energy system. Current studies that investigate the benefit of savings either focus on a specific technology [91,100–103] and investigate the benefits of this or see savings in a larger picture in combination with the installation of production technologies [75,104,105].

Heat savings are extremely important in a future smart energy system. In Lund et al. [99], it was investigated to which extent heat should be saved rather than produced and to which extent district heating infrastructures, rather than individual heating solutions, should be used in future renewable smart energy systems. Based on a concrete proposal to implement the Danish governmental 2050 fossil-free vision, the paper identifies marginal heat production costs and compares these to marginal heat savings costs for two different levels of district heating. On the overall Danish level, a suitable least-cost heating strategy seems to be to invest in an approximately 50% decrease in net heat demands in new buildings and buildings that are being renovated anyway. The implementation of heat savings in deep energy renovations that would not have been carried out anyway for other purposes at present hardly pays from a socio-economic perspective [106].

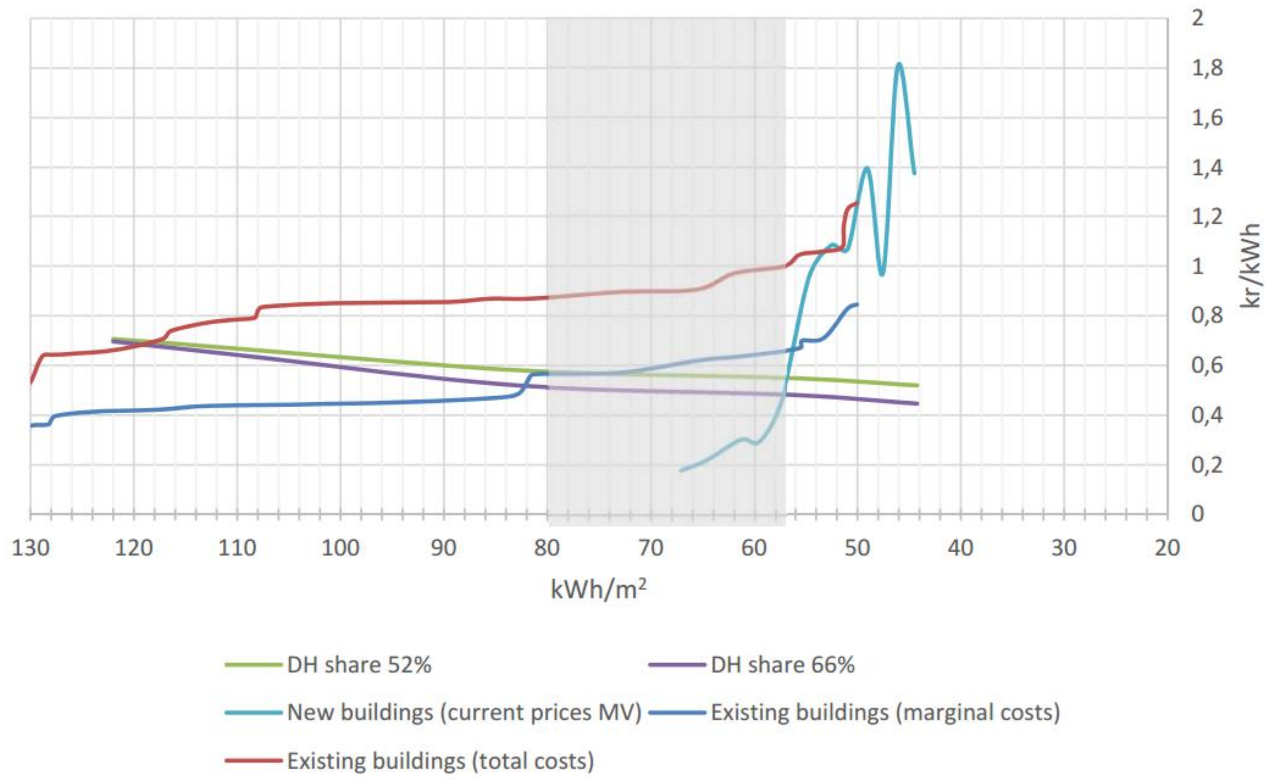

Figure 38: Marginal cost of heat production in the overall energy system in year 2050 compared to the marginal cost of improving the energy efficiency in a new building, an existing building (total costs) and an existing building being renovated anyway (marginal costs). New buildings are here represented by a 150 m2 single-family house and existing buildings as the total m2 of single-family houses, farmhouses and terrace houses. Both are shown as a function of the average heat demand per unit in the buildings.[40,99]

Further, the analysis highlights the importance of identifying long-term heating strategies since least-cost solutions require a long period of implementation. First, savings should mostly be implemented when buildings are being constructed or when renovations are being carried out anyway, which requires several decades to cover the building stock. Second, a suitable district heating infrastructure should be developed and adjusted to low-energy buildings, which also calls for a long time horizon [99].

In smart energy systems and other integrated energy systems which emphasise the combination of and coordination between different parts of the energy system, the system influences the performance of energy savings initiatives. Here, it becomes important to identify the energy system's effect on savings, and possible synergies between various types of savings across different sectors [105].

The system perspective is very important when discussing energy savings. As the benefits of replacing roofs and other initiatives to reduce the heat demand differ depending on the energy system, it does not make sense to talk about demand reductions without having a clear idea of how the benefits depend on the system. In a smart energy system, a high number of heat saving initiatives in district heating areas might not perform as expected due to the high level of CHP. A system perspective and an understanding of possible synergy effects therefore help identifying strategies for a better performance of, for instance, heat savings [105].

Some uncertainty is related to the fact that there are not many studies on the system consequences of different types of energy systems. The study [105] is to the authors' knowledge the only study that tries to identify system relations between different energy saving types, and it is only done in a current Danish energy system. Further studies should focus on the synergies between energy savings in future 100 % renewable smart energy systems. These systems are even more integrated than the above mentioned study [105], where transport and gas grids are integrated with the electricity and thermal grids. Other studies could also regard other countries applying the methodology suggested in [105].

4.4. Heat pump/Organic Rankine cycle reversible units (New heat infrastructures and systems)

The concept of reversible heat pump/organic Rankine cycle reversible units is proposed coupled with advanced thermal storage. The system gives the ability to generate electricity back to the grid based on stored heat produced through the heat pump operational mode. This new reversible unit concept could not only improve the residential thermal supply system efficiency by 30-40% [107] - when compared to simple heat pumps with sensible water storage - but will also extend the current intraday flexibility of heat pumps to a far wider range of flexible use while preserving the way of living and comfort of the consumers.

Carmo et al. [108] investigated the real life operational performance of 300 heat pumps located in Denmark. They compared the various methods by which heat pumps are integrated in households, the various types of heat pumps (brine-water, air-water/brine etc.), and the integration with the heating system in the houses. The findings give a detailed insight into the actual performance of heat pumps subject to real life conditions.

Dumont [109], Carmo et al. [108] created a detailed dynamic model of a passive house coupled with a reversible unit proving the feasibility of the combined system and the operational ranges in which the system is relevant.

The system combines three main R&D areas (heat pumps, thermal storage and Smart Grid control strategies) with low-temperature power generators (LTPG). The system is mainly considered for houses outside the district heating areas and could potentially aid the extensive replacement of oil furnaces. Furthermore, the system can facilitate major cost savings and efficiency improvement through standardized installation, remotely monitored operation, and supplementary Smart Grid services. Dual mode operation of heat pumps for both heating and cooling is also a possibility [110]. The use of low global warming potential (GWP) working fluids in ORCs and reversible cycles is considered by multiple authors [110–113].

Heat storage systems such as stratified storage tanks and thermal storage materials are typically considered for these systems [107,114,115].

A typical system topology is shown below [109] – the core of the system is a reversible compressor/turbine unit:

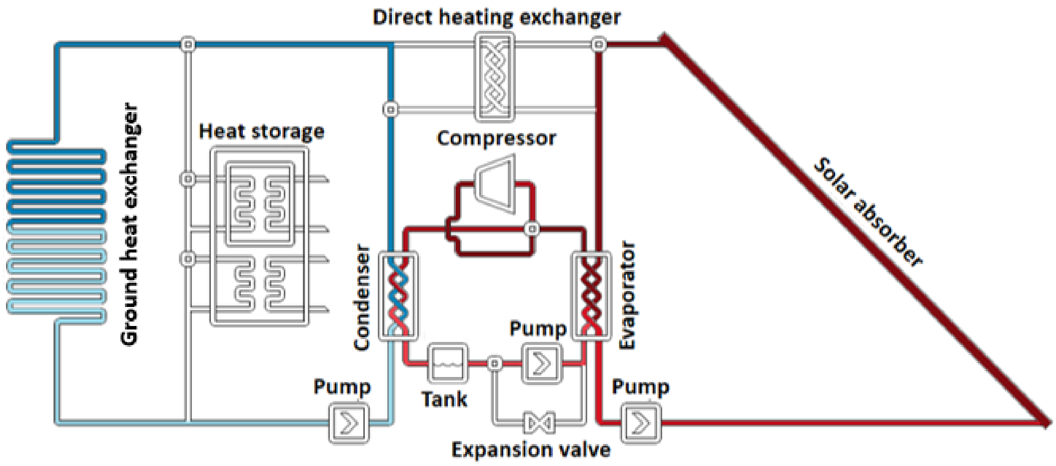

Figure 39. Typical system typology of reversible heat pump

National and international projects such as iPower [116], ecogrid Bornholm [117], DREAM [118], CITIES [119] and EDGE [120] comprise possible frameworks for this technology.

4.5. Waste heat from processes in industry and commercial buildings (Waste heat from industry)

With a low-temperature district heating network with supply and return of about 50/20°C, there is a much higher potential for usable waste heat from industrial processes and from cooling processes in commercial buildings (e.g. supermarkets). Even though the waste heat may be available all year round, it is not controlled by the heat demand in the district heating system and it is also a local input. Therefore, a district heating system that makes use of local waste heat from processes in commercial buildings is a much more complex type of district heating system that requires detailed dynamic performance investigation and planning. It does, however, also enable a central thermal storage facility which is both low cost and able to integrate such sources.

Based on some test trials in supermarkets in France and the UK, figures show that supermarkets can be flexible with around 60-80% of their normal cooling capacity for around 20 minutes if managed properly and that they can react within seconds. Supermarkets can improve the flexibility of electricity grids and heating grids. When it comes to electricity grid load shedding, supermarkets can react quickly by adjusting their electricity consumption (e.g., for refrigeration, defrosting etc.). Supermarkets can provide both short-term response (response to frequency change in grid within 5-10 seconds) as well as longer and scheduled electricity consumption adjustments (e.g., during peak hours). Supermarkets can help with excess electricity production since approx. 60-70% of the installed compressor capacities are unused for most of the time.

When it comes to integrating supermarkets with the district heating network, there is a lot of heat that can be recovered from cooling processes and also the unused capacity of the compressors can be used as a heat pump capacity. A pilot store in the south of Denmark was used and monitored to see the advantages of such systems. The results were as follows: DH grid losses are minimized as the on-off cycles are reduced especially during summer time, the heat loss from the refrigeration system to the ambient has been reduced considerably (40%) and turned into a revenue stream and the heat produced by the supermarket in the case is equivalent to the demand of 16 standard homes and it saves the environment for an equivalent amount of CO_2.

4.6.Further research

Zero energy buildings (Energy efficiency in thermal system)

The concept of Zero Energy Buildings (ZEBs) (and Zero Emission Buildings) is still not clearly defined. Literature on the topic has primarily been published during the last years dealing with the definition of buildings being net Zero Energy Buildings over a particular period of time [121–125]. There are various balancing methods for ZEBs and it is therefore important to define which parameters have been chosen to measure the zero energy performance.

When designing energy supply systems for ZEBs, several requirements and frame conditions have to be considered. Figure 40 gives an overview of the different fields which are involved.

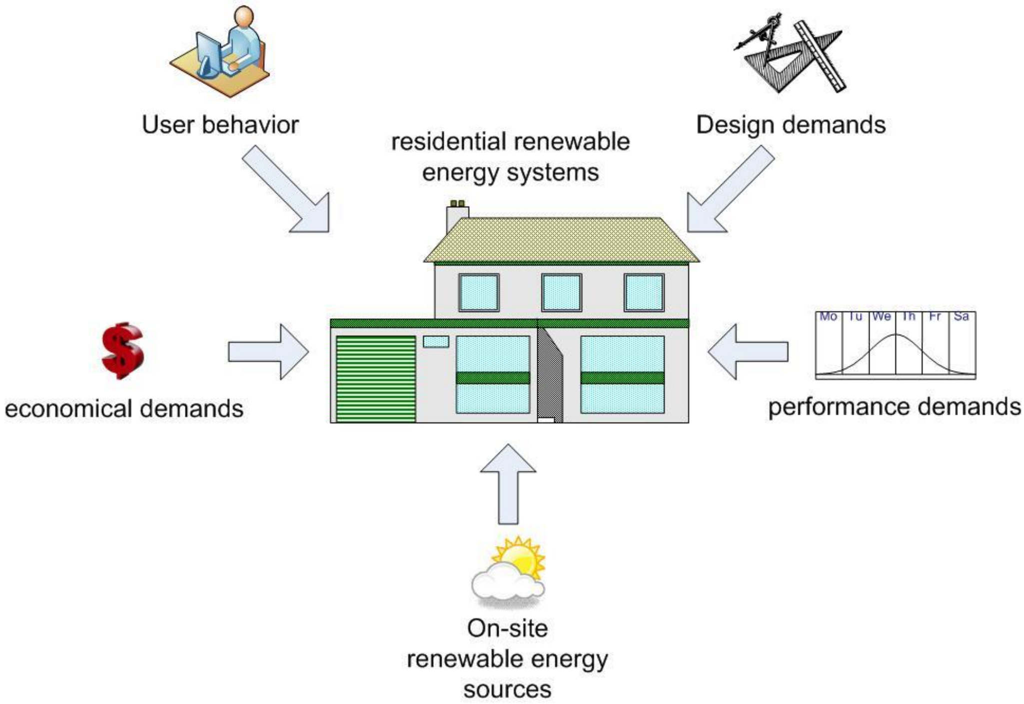

Figure 40 requirements and frame conditions for the integration and optimization of renewable energy systems (RES)

To enable the optimization of the energy supply system, while taking these side constraints into account, an optimization methodology, e.g., in the form of a computer programme, would be desirable. A wide range of computer models exist which can assess and design energy supply systems for buildings. Most of the existing models address the system design in the context of a regional or national level and therefore it is impossible to investigate a single supply system in detail [119,126–128]. Furthermore, the large majority of the programmes or optimization methodologies presented in the literature are focussed on the partly integration of RES into existing local networks and on a single energy form, as done by [129–131] and observed by [127]. Also, the majority of the programmes only have certain technologies or very specific system configurations implemented, which excludes the possibility of choosing the optimum between a wide range of different system designs and scenarios [132,133]. Therefore, designers of Net Zero Energy Buildings often use trial and error methods for each specific building to arrive at the optimal system design and several researchers state that there is a need for an optimization methodology for Low and Zero Energy Buildings using renewable energy sources [134–136].

The special requirement for such an optimization framework is that a full integration of RES is necessary and that both heat and electricity generation have to be considered and dimensioned in a coupled way due to hybrid technologies, such as integrated photovoltaic and solar thermal (PVT) collectors or heat pumps.

A possible solution was provided by [137] with the proposal of an energy systems engineering framework which allows choosing an optimal design of available energy technologies taking into account building energy demands and further constraints. However, the methodology presented was developed for commercial buildings. Further modification and adaptation to 100% renewable energy supply systems for residential ZEBs are necessary. Milan [138] provided inputs to this and developed an optimization framework of the supply systems for general domestic buildings. Also Fabrizio has done a lot of research on this subject and has developed a multi-energy system model based on the energy hub concept, which allows an optimization involving the implementation of user behaviour and the variability of the energy sources [132,133,139].

It should also be mentioned that, except for the two above-mentioned researchers, the work published on the development of optimization approaches for low energy buildings is mostly based on genetic algorithms or highly non-linear complex problems, including the modelling of the whole building together with the supply system [134,136,140]. These models are computationally intensive and the calculation of a one-year performance would take up to two months on the newest processor engines[140]. In [138], an advanced and fast optimization framework was developed.

Reversible heat pumps (New heat infrastructures and systems)

An important instrument for reaching extreme penetration levels for intermittent renewables and for achieving optimized ZEBs could be organic Rankine cycles operated at low and medium temperatures [141–143]. The HP2Grid functionality refers to the ability of the system to generate power back to the grid from the heat pump’s dual thermal storages.

Although “reversible” HPs are not a novelty and have been considered since 1924, reappearing after the oil crisis of the 1970s, the scientific body has recently showed increased interest to review and improve low capacity power generators (LCPG) [144,145]. Current research on LCPG has not proven to show efficiencies higher than 10% (18) in “reversible” heat pumps and 2-4% in thermo electric devices (TED).

Significant efficiency improvement is not expected for LCPGs for residential purposes, as they involve lower temperatures and lower turbo machinery efficiency than large-scale power generators. However, the overall residential thermal system efficiency and flexibility are expected to improve when compared to simple heat pumps with water energy storage. Thus, the novelty is to develop the optimal integration of residential thermal energy systems to support renewable energy integration, through component interaction and dynamic modelling improvements.

Low-temperature space heating and domestic hot water (DHW) supply system (Improved district heating and cooling)

It is possible to reduce the total energy use for space heating of new buildings to a level equivalent to the energy use for domestic hot water heating. Consequently, a better balance is obtained between the energy needed during summer and winter [146]. In this way, the total energy use, being at a relatively constant low level, can be delivered by heat recycling or RES at a lower cost. The reduction of heating demands of existing buildings may be exploited by the district heating system in the following two ways:

- First, the capacity of the district heating grid and production units allows more buildings to be connected to the same grid.
- Next, the insulation of existing buildings means that comfort is achieved by lower supply temperatures. This will also reduce grid losses and will increase the recycling of heat and the efficiencies of the production units.

The change in temperature demand may be further improved by introducing heating systems that can use supply temperatures of 40° C and cool down the district heating water to near room temperature (20-22° C) [33,147]. Floor heating or wall heating with an average water temperature just a few degrees higher than room temperature is a possibility [148]. Oversized water heating panels with a proper flow control system to cool the water to a low temperature may alternatively be used.

By using substations without storage of DHW at the end-user and pipes with only a small volume between the heat exchanger and the taps, the hot water volume is so small that the potential problem with legionella bacteria is minimised. Therefore, it may be possible to use a 40-50°C supply temperature of DHW. In this way, the temperature level of the district heating supply to the buildings can be as low as 45-55° C [149]. In large buildings, local DHW heat ex-changers are used to ensure a very small volume of DHW supply pipes. Heat supply for space heating and the DHW heat exchangers are provided by a circulation pipe in the building.

Intelligent control and metering of the network performance (ICT, meters, advanced monitoring)

Decentralised intelligent metering may be used in order to get a close link between the power and the energy used by the buildings for the continuous commissioning and the payments. Wireless gathering of heat meter readings over short time intervals makes this possible. This may also include metering the sale of surplus heat from, e.g., solar thermal from the individual building to the grid as well as motivate to better cooling at the consumers [33].

District heating pipes with improved insulation (Improved district heating and cooling)

By use of twin pipes with the supply pipe in the centre and the return pipe located at the isotherm equal to the return temperature, the heat loss can be reduced and the heat exchange between supply and return pipes can be eliminated. Insulation materials may be improved by adding pacifiers to reduce the heat transfer caused by thermal radiation [33,150].

Smaller pipe dimensions (Improved district heating and cooling)

By reducing the peak flow rate in the distribution network, the pipe dimensions can be reduced. This can make it possible to use twin pipes with a factor 2 lower heat loss coefficient than two single pipes. By use of low temperature and small pipes, it is possible to reduce the distribution of heat losses compared to existing systems by a factor 4. The use of small pipes increases the pressure requirement but this may be solved by the use of local pumps in the network or buildings [33,150].

Intelligent control of the heating of buildings and peak shaving (Energy efficiency in thermal system)

The intelligent control makes use of weather forecasts to calculate the need for heating in each room and this information is used to control the operation of the heating system [33]. This is especially relevant for floor heating installations, where a weather forecast based control of the floor temperature can improve the indoor environment. Moreover, the efficiency of the heating system improves, as the thermal capacity of the concrete deck may be allowed to discharge before the occurrence of excess solar gain. The peak load for space heating during a day may be reduced by use of higher thermal capacity of the building and by using space heating systems with a peak shaving control system. This may be realised in a simple way by use of a maximum flow controller [151]. Alternatively, an intelligent control system based on 24 h weather forecasts may be used to calculate the required need for space heating and to feed the individual rooms with the predicted energy for heating.

District cooling demands (Improved district heating and cooling)

It is important to understand more about the cooling demand and supply in the future since this could be an area where greater energy reductions and efficiency in the system could be achieved [152]. Recently district cooling research has been done in Denmark and this is presented in the report [153]. This report covers numerous aspects of cooling in Denmark including the current and future cooling potentials (split into types of cooling and location), descriptions of existing district cooling and descriptions of the technical, financial and organisational solutions. In the report it is assessed how much cooling could be met by district cooling and what the barriers are to achieve this. In 2015 an analysis was completed in the IDA Energy Vision 2050 where district cooling was included in the energy system for 2050 [40]. Further efforts should focus on how these barriers to increase district cooling could be removed.

5. Gas grids, infrastructures and technologies

In this section, the state-of-the-art research for the gas sector in Smart Energy is described. Table 8 below presents a brief overview of the main topics in the state-of-the-art research. The main research gaps are also presented in Table 8. Although some areas are currently being researched, research gaps may occur in the areas; thus, they are included in both columns in the table.

Table 8: Summary of key areas included in state-of-the-art Smart gas research, and research gaps

State-of-the-art topics	Main research gaps
Gas grids, new infrastructures, storage and systems	Gas grids, new infrastructures (biogas integration, distribution of hydrogen and syngas)
Electricity to gas	ICT, meters, advanced monitoring
Electricity to liquid fuel	

A detailed description of the state-of-the-art research in the gas sector is presented below, beginning with a summary.

Summary of the state-of-the-art

The gas grid will play an important role in the future renewable energy systems as today's natural gas network will have to adapt to different types of renewable gases. Moreover, as the biomass resources are scarce, new ways of producing gases and liquids will have to be incorporated with the grid itself but also as accompanying storage facilities. The gas grid can contribute to the smart energy system by providing long-term energy storage of electricity through the conversion of power-to-gas and power-to-liquid. These conversion technologies are furthermore important as they enable the smart energy system to interact with those parts of the transport system that cannot make use of electricity. This section summarizes different components of the smart gas grid, including gaseous products of interest, grid types, production cycles such as power-to-gas and power-to-liquid for transport and balancing purposes, and finally different storage options. This connection and interaction between the smart electricity grid and the smart gas grid through the storage of electricity in the form of gas or liquid fuels are important aspects of systems with a high share of renewable intermittent energy. The grid interaction offers an opportunity for long-term energy storage that is much needed. By establishing this interaction, the construction of new transmission lines can be avoided and cross-sector integration is enhanced.

The main research gaps include gas for transport, the distribution of hydrogen and syngas, and the interaction of the gas grid with other energy sectors.

5.1. Gas types and grid transmission (Gas grids, new infrastructures, storage and systems)

Different types of gases that will be a part of the renewable energy system are biogas, synthetic gas (syngas), synthetic natural gas (SNG), hydrogen and CO_2. The existing natural gas infrastructure is well developed and it serves as a storage buffer itself. The first priority is to utilise this infrastructure in the future and investigate if this network can handle different gas characteristics. Upgraded biogas and SNG can be transported with the existing natural gas network. SNG is already methanated synthetic gas; thus, it can be transported directly via the natural gas grid.

In the case of biogas, it is required that the biogas is upgraded and purified to the required quality of the grid gas [154]. Several upgrading technologies are commercially available and the technology has been used for 20 years [155,156]. The upgrade of the biogas can be done with hydrogen produced by water electrolysis and methanation of the CO_2 part of the produced biogas, which will enable the direct use of the biogas in the network. There are some differences when it comes to the injection of upgraded biogas to the natural gas grid depending on the transmission or distribution network scale. Distribution networks are smaller, meaning that there could be problems with the injection of upgraded biogas as the biogas plant operates on constant load. Therefore, in the case of large-scale biogas injection, it should be done on the transmission scale rather than through distribution [157] otherwise the grid operator must pump the excess of gas from the distribution grid by compression to the transmission grid. A Danish project has looked into the relevance of establishing a biogas grid for distribution to CHP plants and its direct connection to the natural gas grid [158]. An overview of different biomass gasification and biogas upgrade technologies including the economic assessment and relevant projects was carried out previously by Danish Gas Centre [159,160].

There has been several studies on the transport of hydrogen in the natural gas network, including the EU project NATURALHY finished in 2009 [161], but also an ongoing long-term project in Denmark on the stability of a NG pipeline with different concentrations of hydrogen up to 20% [162]. The mixture of hydrogen and natural gas can be transported in the current pipeline with maximum 20% hydrogen. In cases of concentrations below 15%, only moderate modifications are needed [163]. However, what the pipeline can handle itself is not aligned with what the connected facilities can handle. Results from previous tests done in Denmark report that a maximum of 2% can be injected into natural gas grids if connected to CNG filling stations and a maximum of 5% if the grid is not connected to CNG filling stations, gas turbines and most gas engines [164]. As the natural gas grid cannot tolerate the high percentage of hydrogen, due to its properties of high percentage of hydrogen and carbon monoxide and the explosive potential of the gas, syngas cannot be transported through a natural gas network. However, there has been research on the potential of tuning the gas to avoid the self-ignition problem [165]. Carbon dioxide transportation through a pipeline network is possible; however, it cannot be done through the natural gas network but with a separate infrastructure [166].

Steps have been taken into upgraded biogas integration in the existing natural gas network. In Denmark, the first demonstration was made in 2011 and four plants were connected to the grid with the injection of around 18 million Nm^3 in the Danish natural gas system [167]. Energinet.dk also reports that another 10 projects are being developed and will potentially be connected to the grid. The Biogas Taskforce has indicated the main barriers to expanding biogas utilisation in the grid and the system, and these are mostly related to the costs, availability of suitable biomass, and policies and regulation [168].

5.2. Storage options (Gas grids, new infrastructures, storage and systems)

Biogas storage/SNG can simply be stored in large metal canisters that can ensure the proper pressure needed for storing these gases. Other available options are washed-out subterranean salt caverns, thick balloons or degassing tanks covered with flexible tarpaulins [169].

There are different available hydrogen storage options such as compressed hydrogen gas storage and liquefied hydrogen storage as the two most developed and large-scale technologies [170]. There are also underground storage options as salt caverns and aquifers [171]. As for the underground storage options, these could be logistically more complex as production facilities would not necessarily be located at the same place as the storage facility. Therefore, an additional transport of hydrogen would have to be established [172]. The syngas can be stored on a daily or relatively short term in the compressed gas storage, and the industrial experiences suggest that there is no excessive diffusion or leakage of syngas if it is not stored for a longer periods [165].

5.3. Power-To-Gas (Electricity to gas, Electricity to liquid fuel)

The Power-to-Gas (P2G) concept converts electricity to the energy-rich gases hydrogen or methane. Hydrogen is the first product from the P2G process and can be used in industry or as a transport fuel if the infrastructure is developed. The further conversion of hydrogen from water/steam electrolysis to methane or SNG is possible, and can be used directly in the existing natural gas grid; for the production of power and heat in CHP plants, or for mobility. The comprehensive overview of the Power-to-Gas technology is given by Lehner *et al* [173] indicating that currently this technology is not economically feasible but in order to achieve the integration of renewable energy and provide long-term storage, it must be developed. Germany has put great emphasis on this concept and there are many ongoing projects including the world's largest P2G plant generating 3 million cubic metres of methane per year [174]. Power-to-gas conversion efficiency is around 70% with high-temperature electrolysis systems [175,176]. The demonstration plants in Germany with existing water electrolysis technology have around 55% efficiency according to the technology developer [177]. The conversion back to electricity is, however, more inefficient (typically around 50% in fuel cell systems) leading to relatively low roundtrip efficiencies [178]. When the power-to-gas systems are installed in an isolated system, they are often coupled with battery or supercapacitor storage to account for the fast fluctuations in renewable energy production [179,180].

The wastewater treatment plant in Avedøre makes biogas from the decomposition of wastewater slurry. In addition to methane, a new biological process, where microorganisms and hydrogen convert CO_2 to methane, is upgrading the biogas so that it can be sent to the Danish gas customers through the natural gas grid. At the same time, the sister project is testing a new technology for the chemical upgrading of biogas. Excess CO_2 from this process can also be converted into methane in the P2G BioCat project [181]. In the Mega-stoRE project, a proof of biogas upgrade concept was done in which the carbon dioxide fraction of biogas was upgraded to pure methane by methanation with hydrogen (see Figure 41 [182]. The developed concept is going to be upscaled in a new upcoming project [183]. Screening of P2G and biomass gasification projects and technologies related to connecting electricity and gas grid is reported by Iskov and Rasmussen [184].

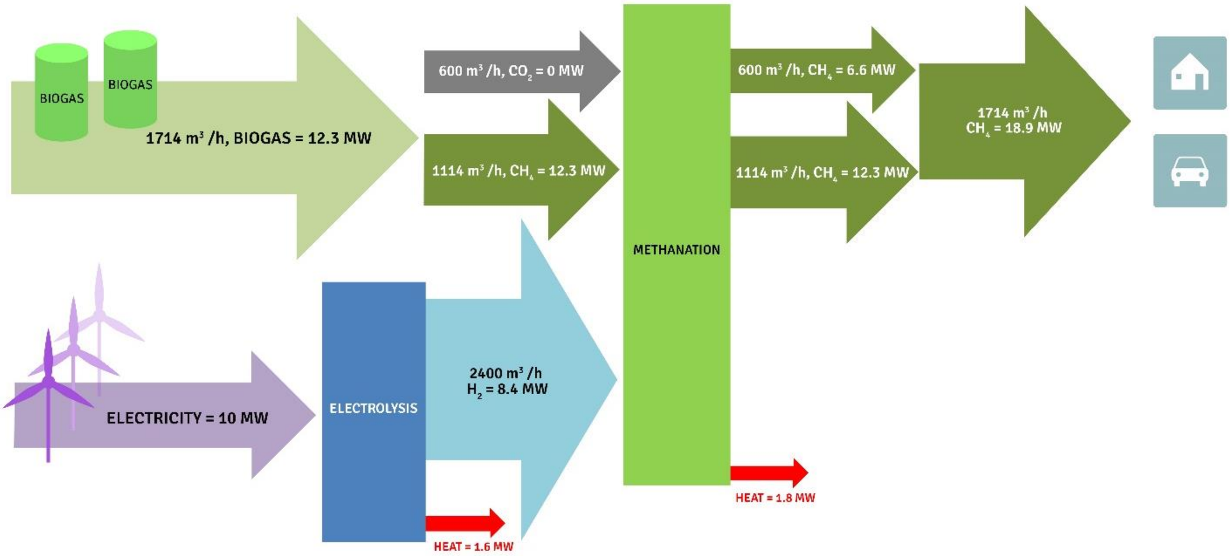

Figure 41 Illustration of energy flows from the MegaStore concept [185].

5.4. Power-to-gas/liquid transport (Electricity to gas, Electricity to liquid fuel)

Power-to Liquid technologies for long-term energy storage in the smart gas grid concept are based on the electrolysis of water as this technology converts electricity into hydrogen that can be further converted to methane or different liquid fuels such as methanol or DME. Methanol or DME can be used in internal combustion engines for transport. Moreover, if desired, with the higher conversion losses, the synthetic gas can be converted to petrol or diesel. This is of great importance as the transport sector is facing big challenges in the future. Even in the case that the electrification of transport is maximized, it is not possible to completely eliminate the dependence on liquid or gaseous hydrocarbons in the transport sector, especially when talking about heavy-duty long distance transport, marine and aviation. In order to achieve the renewable energy goals, even if the biomass potentials are utilized for fuel production in the form of biofuels, there is still a part of the demand that cannot be met [186].

5.5.Further research

Gas for transport

In some of the scenarios, gas for transport could become necessary for the green transition and further research and development areas should focus on 1) technological development, as there are no existing gas vehicles over 350 horsepower and there is less torque in gas vehicles than petrol and diesel cars, and 2) developing infrastructure.

Distribution of hydrogen and syngas (Gas grids, new infrastructures, storage and systems)

The limits of transmission of hydrogen in the natural gas grid are related to the pipeline materials, the properties of hydrogen and the connected facilities. More case studies that will assess the impact of the hydrogen and gases with a high share of hydrogen in volume mixture on the existing pipeline system need to be conducted, including a cost analysis of managing hydrogen integration in the gas grid. The maturity of the electrolysis technology to produce renewable hydrogen goes from commercially available alkaline electrolysers to solid oxide electrolysis cells (SOEC) that are still on the R&D level [187]. Overall, the main challenges are the costs of hydrogen production, the required upscaling of the electrolyser capacity

[188,189], and the low concentrations that can be injected to the existing gas grid. When it comes to syngas transport, due to the limitations, the new infrastructure needs to be developed and the cost data is very difficult to obtain. Furthermore, the transport of this gas mixture is not heavily investigated and reported in the literature and this is the main research gap that needs to be eliminated.

Gas grid interaction with other grids (Gas grids, new infrastructures, storage and systems)

There is a need for a more integrated research approach to different Smart Grids. The concepts developed do show this tendency, but there is no large extent of literature that explores the interactions between different grids when the Power-to-Gas or Power-to-Liquid technologies are deployed. The incorporation of gas generation, transport fuel conversion and storage will be beneficial with a high share of renewable technologies, but more onsite testing of this technology will bring a better understanding of its effects on different Smart Grids. Further development and commercialization of the hydrogenation technology are crucial to its high deployment.

6. Cross-cutting interaction between the three sectors

In this section, the state-of-the-art research into the cross-cutting interaction between the three sectors in Smart Energy is described. Table 9 below presents a brief overview of the main topics in the state-of-the-art research. The main research gaps are also presented in Table 9. Although some areas are currently being researched, research gaps may occur in the areas; thus, they are included in both columns in the table.

Table 9: Summary of key areas included in state-of-the-art Smart gas research, and research gaps

State-of-the-art topics	Main research gaps
GIS	Energy system analysis
Energy system analysis	Improved sector interaction
Inter-sector technologies	ICT, meters, advanced monitoring
Large-scale penetration of renewable energy	Inter-sector technologies
	Large-scale penetration of renewable energy
	Biomass mapping (i.e. location, amounts, types, costs)

A detailed description of the state-of-the-art research in the cross-cutting of sectors is presented below, beginning with a summary.

Summary of the state-of-the-art

The transfer from a fossil fuel-based to a renewable energy system requires greater flexibility in future energy systems, which will also introduce greater complexity in existing energy systems. This is not only in terms of intermittency but also in terms of the necessary balance between electricity and heat supply units, such as CHP, power plants, and boilers. This becomes even more complex with the addition of mobility, fuels, and heat pumps, which are often necessary to create even more flexibility between the various sectors of the energy system.

A crucial element in this complex transfer to renewable energy is to show coherent technical analyses of how renewable energy can be implemented, and which effects renewable energy has on other parts of the energy system. Such an analysis requires computer tools that can come up with answers to these issues by modelling defined energy systems. It is time consuming to create new tools for each and every analysis; hence, if feasible and accessible tools exist, these should be used.

Recent research shows that merging the heating and electricity sector from a system level is important in order to create a fuel efficient energy system that is economically and environmentally feasible [43,79,104,178,190–194]. In fact, connecting the electricity and heating sectors can lower overall costs and increase the value of wind power [195].

In grid stabilisation tasks, to secure and maintain voltage and frequency in the electricity supply as well as to involve flexible technologies, such as CHP and heat pumps, it has been found that it becomes essential to include other flexible solutions such as the electrification of transport (batteries and electrolysers). Such an involvement becomes increasingly important along with the acceleration of the share of RES.

In this light, it has been shown that net zero buildings are not a cost or resource effective option for the heating sector [196]. It is more cost and energy effective on the system level if the heating sector and the electricity sector can be interconnected by using technologies such as large thermal storage and large-scale heat pumps supplying heating for district heating networks.

6.1. Large-scale penetration of renewables and 100% renewable energy systems (Large-scale penetration of renewable energy)

For the feasible storage and management of intermittent resources, it is necessary to have sector integration and to identify the synergies in all parts of the energy and transport system. Smart energy assessments have been carried out in Denmark in order to understand how the entire energy system can use large-scale renewable energy and shift to 100% renewable energy systems.

A systematic methodology has been developed and applied to take into account key societal challenges and to thoroughly understand how the gaps in the current research trajectory can be eliminated. Coherent integrated scenarios have been done looking forward to 100% renewable energy in 2050 using integrated hourly energy system analyses [38,197–199].

The IDA Climate Plan 2050 from 2009 did research and modelling into a highly renewable Danish energy system and laid out a roadmap (incl. transport) on a scientific basis to reach 100% renewable energy in all sectors in the Danish context [197,198].

In 2011 in the CEESA project, the smart energy system approach was defined. In the project, analyses were done on the technical and economic implications of a 100% renewable system in Denmark. The project addressed Danish scenarios with a particular focus on renewable energy in the transport system in a context with limited access to bioenergy. Various 100% renewable energy and transport systems were designed and analysed and these formed the basis for the development towards the first set of smart energy system designs.

The smart energy system approach includes a substantial merging of the different energy sectors and a modelling of the entire energy system on an hourly basis including electricity, heat, cooling, industry, and transport. This leads to the identification of a more fuel-efficient and lower-cost solution compared to the traditional approach of individual sectors. The smart energy system concept harvests storage synergies enabled in the cross-sectorial approach and exploits low value heat sources in 100% renewable energy systems [151,152]. Higher penetrations of fluctuating renewable resources are enabled, such as wind power, photovoltaics (PV), wave power and run-of-river hydro power, at the expense of fossil fuels or bioenergy.

The CEESA project made a more complete picture of the smart energy systems concept; however, the concept is the result of more than 20 years of research in the Danish context. Denmark is one of the most successful showcases for renewable energy with cost and resource effectiveness.

Since CEESA, extensive analyses have been done in a number of research projects focusing on 1) The role of smart gas grids and renewable electrofuels/synthetic fuels for transport, as well as 2) The role of district heating in the Heat Roadmap Europe 2050 studies and a large research centre for 4th generation district heating [79,191,193,194].

The energy system analyses are conducted using the advanced energy system analysis tool EnergyPLAN. The main purpose of the tool is to assist the design of national or regional energy planning strategies on the basis of technical and economic analyses of the consequences of implementing different energy systems and investments. The tool quantifies the most technically and cost feasible approach to achieving a 100% renewable energy system for a region or country and the road map to such systems. EnergyPLAN has been developed and expanded on a continuous basis since 1999 at Aalborg University, Denmark. 12 versions of EnergyPLAN have been created, and the current version can be downloaded free from www.EnergyPLAN.eu.

6.2. GIS mapping of resources (GIS)

The cross-cutting interaction of energy sectors in smart energy systems requires a strong focus on the location of both energy supply and demand. The reason behind this is that the concept of smart energy systems focuses on utilizing renewable energy sources, for which the availability is highly dependent on geography. In regards to demands, the geographic location becomes increasingly important, as many smart solutions are decentralized or local.

Mapping of renewable energy resources

In regards to mapping renewable energy resources in Smart Energy, the focus is primarily on wind power, solar energy as well as different types of biomass resources. An important consideration when mapping biomass is to determine the proximity of the biomass from its collection point to its final destination for energy conversion. The assessment of proximity should be coupled with an assessment of the amount and type of biomass that is recoverable from the different locations. Understanding the amount, type and proximity of biomass available will help to determine the location, type and size of the energy conversion technologies that will be built to utilise the biomass types. In addition, this knowledge helps to understand the costs of handling, transporting and utilising the biomass. Geothermal energy and wave power are important as well. An area related to resources is high-temperature heat sources from industry and power production, as well as low-temperature heat sources for heat pumps.

More specifically some important factors that have been considered in previous mapping and Smart Energy research and development have been: the potential for onshore wind power, mainly with a focus on land-use restrictions and access to infrastructure [200–202]; offshore wind energy with a focus on estimating costs for foundations based on sea depth [203]; photovoltaic potential on rooftops in urban areas [204–207]; different biomass potentials [208–211]; wave energy potential and costs [212]; low-temperature geothermal energy for ground source heat pumps [213], and excess heat sources from industrial process to be used for district heating in a European context [79].

In regards to mapping energy demands, it is common to divide energy demands into heat, electricity, transport and industrial demands. Besides these demands, a focus on storage options is also essential in regards to mapping and analysing smart energy systems.

In a Danish context, electricity demands have not been a target for mapping as these are typically connected to the national electricity grid and are therefore not as locally dependent as heating. This could very well change in the near future, due to requirements to save residential electricity consumption of households in a central national database.

6.3. Analysing the smart energy system (Energy system analysis)

It is important that the analysis of the smart energy system compares all alternatives for both existing and future energy systems. This is done using computer modelling tools. Energy strategies are developed based on the consequences of different options, rather than on individual measures that must be implemented. In this light, the analysis must be able to consider a high number of alternative energy system configurations. Analyses must consider radical technological and institutional changes, for example currently wind turbines do not contribute to grid stabilization; however, in the future they might.

There are numerous tools available to model the integration of renewable energy. However, the level of integration into the different sectors differs between the tools. The different functionality of the tools determines the options for increasing flexibility within the energy system, which in turn increases the renewable energy penetrations that are feasible. Some examples of how the tools differ are explained here. For example, currently the tools that consider the district heating as well as the electricity sector are BALMOREL, GTMax, RAMSES and SIVAEL. Tools that account for all aspects of the heat sector (including CHP and thermal storage) and electricity sector are, among others, E4cast, EMINENT, and RETScreen. Tools that include the heat, electricity and transport sector in the form of EVs are, among others, PERSEUS, STREAM, WILMAR Planning Tool. MiniCAM and UniSyD3.0 include hydrogen in the transport sector.

Only seven tools have previously simulated 100% renewable energy systems. These include EnergyPLAN, Mesap PlaNet, INFORSE, H2RES, Invert, SimREN and LEAP. Four of these tools (EnergyPLAN, Mesap PlaNet, H2RES, and SimREN) use time steps of 1 hour or less, while the others use annual time steps. As a result, if the objective is to optimize the system to accommodate fluctuations of renewable energy, the tools using 1-hour time steps are more beneficial than the others.

6.4. Electrofuels (Inter-sector technologies)

It is crucial to locate solutions that integrate transport and energy systems, as they enable the utilisation of more intermittent renewable energy in both the transport and the electricity and heating sectors. This integration also enables a more efficient utilisation of the biomass resources without putting a strain on the biomass resource.

Research in Denmark has shown that it is only possible to propose a coherent sustainable development in transport, if transport is analysed in the context of the surrounding energy system and resource potentials [214]. The increasing international focus on the transport sector is mainly centred upon biofuels. Biomass is, however, a limited resource that cannot introduce a sustainable path for transport on its own.

In the long-term planning for 100 per cent renewable energy, biofuels for transport play an important part in combination with other equally important technologies and proposals. A 100 per cent renewable energy transport development for Denmark is possible without affecting the production of food, if biofuels are combined with other technologies. These include savings and efficiency improvements, intermittent resources, electric trains and vehicles, hydrogen technologies and more. It is, however, necessary to integrate the transport sector with the remaining energy system. These challenges can only be met by including planning for this long-term goal in the shorter term solutions.

Research suggests that electricity is the most efficient method of supplying transport fuel in the future [215]. Whereas energy dense fuel is required for other applications, such as long distance driving or for heavy-duty transport such as trucks, then hydrogen is the most efficient way to supply these vehicles. However, in the short term, based on the production costs only, hydrogen is an expensive way to supply this energy dense fuel. These costs are likely to be even more significant when additional costs relating to hydrogen are taken into account, such as hydrogen vehicles and their infrastructure. Therefore, it is likely that some form of gaseous or liquid based fuel will be necessary to supplement electricity in a future 100% renewable energy system. According to the results of previous studies conducted in Denmark [216–218], the most attractive option at present is liquid fuel in the form of methanol/DME. Producing methanol/DME is more efficient than methane and it is anticipated that the cost of adjusting existing infrastructure to methanol/DME is relatively low. However, there is a potential for using gaseous fuels in the transition period or for niche purposes.

A promising example of integrating the electricity, gas and transport sectors is through the Power-to-liquid concept. This comes in different system topologies, but as in the case of P2G, it has the first step of converting electricity via electrolysis to hydrogen (**Error! Reference source not found.**). The hydrogen is then used either for boosting gasified biomass in the hydrogenation process or merged with CO_2 emissions for point sources such as energy or industrial plants and further converted to desired fuels. These fuels are called electrofuels or more precisely bio-electrofuels and CO_2-electrofuels [219,220].

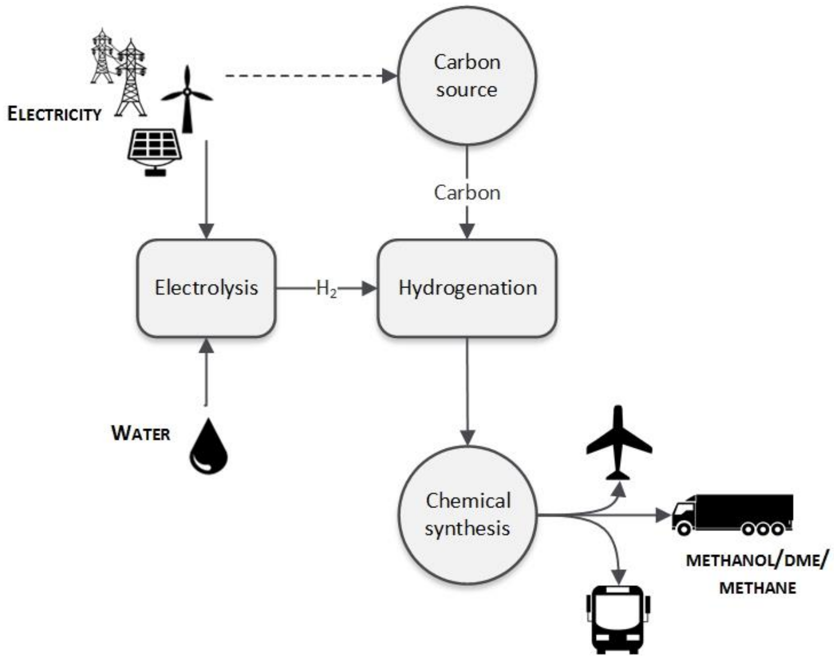

*Figure 42 Electrofuel production flow diagram for biomass hydrogenation and CO_2 hydrogenation pathways. *Carbon source is either biomass gasification or CO_2 emissions. Dotted line is used only in case of CO_2-based electrofuels [217].*

While P2G technology is more present on the demonstration scale, there are only two plants producing electrofuels based on CO_2 emissions. The first emission-to-liquid plant (ETL) was commercialised in 2011 in Iceland [221] and the second one was inaugurated in late 2014 in Germany [222]. The latter is the first plant to integrate high-temperature electrolysers in the production cycle. Bio-electrofuel production via thermal biomass gasification has not been demonstrated yet, even though technologies in the production cycle are demonstrated and in some cases commercialized. The P2G option, where biogas is upgraded to methane by methanating the carbon dioxide part with hydrogen, is an already demonstrated concept in Denmark and will be further investigated in new projects[182,183,223].

Previous research has shown that electrofuels are an important part of the future energy systems and that they can be used in the transport sector due to the bioenergy resource limitation [214,215,224–227]. Electrofuels are an important part of Smart Energy as they offer a solution for meeting different fuel demands whilst providing flexibility to the system. The flexibility created due to the conversion of intermittent electricity to gaseous or liquid fuels is important as it interconnects the electricity, gas and transport sectors. Furthermore, the fuel production facilities produce excess heat, that allows further integration of the fuel production and heating sector. Therefore, further development of the production processes for these fuels is crucial for their deployment in Smart Energy systems.

6.5. Smart liquid grids – hydrothermal liquefaction (Inter-sector technologies)

Hydrothermal liquefaction (HTL) is a direct thermochemical liquefaction technology, by which solid biomass or organic material is converted into a liquid biocrude, with side streams of gas, solid and water soluble products. HTL can be linked to the electricity grid directly through CO_2 stream and indirectly through the AD or SCWG of the water phase, as indicated below.

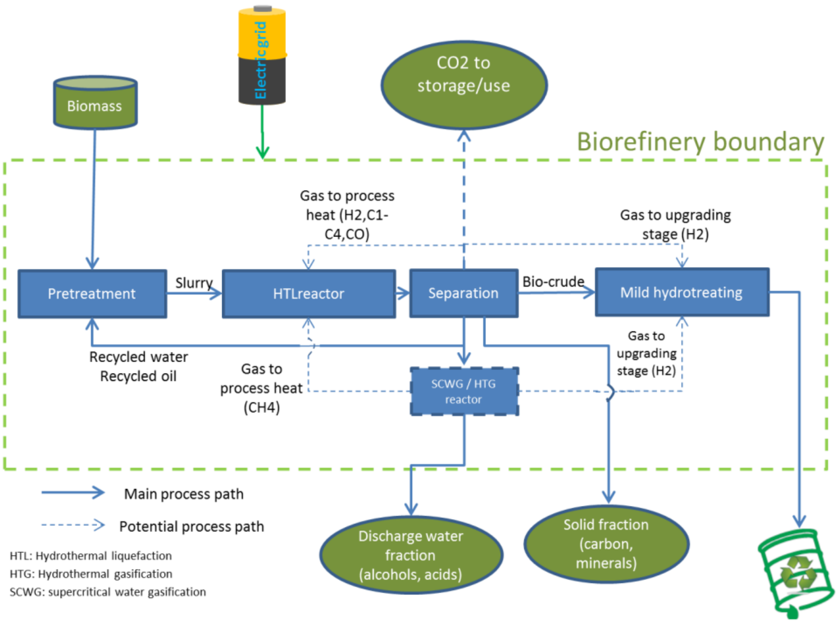

Figure 43 Generic schematic of an HTL plant and its boundaries to electrical grid or fuel production processes.

The biocrude can by hydrotreated to transport fuels or commodity chemicals. The process is able to convert all types of organic material, including lignocellulosics, agro-industrial wastes and aquatic biomasses. The type of biomass influences the composition and yield of biocrude. Normally, a major part of the gas product is CO_2, which can be utilised for electrofuels or other purposes. Hydrogen and other light hydrocarbon gasses form the remainder, and this can either be used for process energy or as a hydrogen source for upgrading steps. The water product phase, which is rich on soluble organics, can be processed in a biogas plant or through super critical water gasification to produce hydrogen.

HTL has been known for decades, but it is only recently that it is emerging as an efficient energy technology in its own right. It was recently identified by a US DOE commissioned report [228] to be the most promising pathway to produce green gasoline, even without utilisation of the gas product stream and with anaerobic digestion (AD) of the water product phase. Research has focused on fundamentals aspects of the conversion, but recently industrially relevant continuous HTL research has been demonstrated by Steeper Energy and Aalborg University. Using wood as an input material, energy conversion ratios of 85% to the biocrude have been documented (Figure 44), corresponding to approximately 40% by mass, and approximately 5% oxygen remaining in the biocrude. Other researchers have published data on the conversion of a wide range of feedstocks, just as research on the integration of HTL with other technologies such as biodiesel[229] or biogas production has been published.

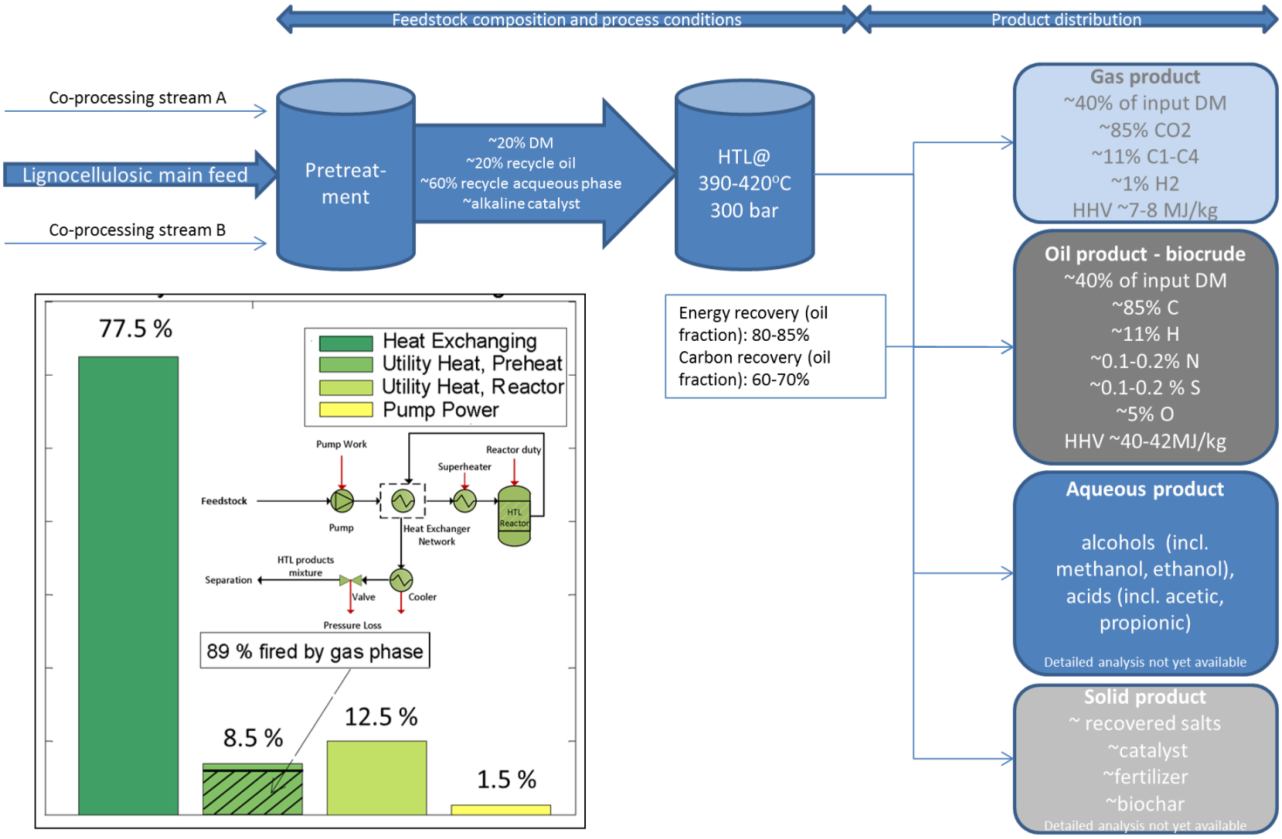

Figure 44 Overview of process steps for continuous HTL, energy and mass balances[230].

6.6. Further research

Modelling of integrated energy systems (Energy system analysis)

There is a need to combine the knowledge relating to the integration of renewable energy in the various sectors of the energy system to minimise overall costs and fuel consumption (fossil or bioenergy). There is a lack of knowledge on (1) what does current research tell us about the integration of renewable energy by combining the different sectors, and (2) what does the actual design of such a smart energy system look like? [38].

The transition to renewable energy and power sources will result in a dependence on stochastic resources, including both generation and consumption. Efficient management of such systems will require research in stochastic optimization and modelling of integrated energy systems; this is explained more in [231] from 2013 about sector integration. Forecasting will play an equally pivotal role for many stakeholders in the energy system and markets.

The challenge in countries with a large penetration of fluctuating renewables calls for new methods for control of the electricity load in future and integrated energy systems and this is explained further in [232] from 2013.

The CITIES project [119] is a current example of how to develop methodologies and ICT solutions for the analysis, operation and development of fully integrated urban energy systems. The aim is to focus on city environments and establish a realistic and concrete pathway to achieve independence from fossil fuels by harnessing the latent flexibility of the energy system through intelligence, integration, and planning. The project aims to identify and establish solutions which can form the background for commercial opportunities within the smart cities environment, and to support the development of these and other smart cities demonstration projects, also including a range of decision support tools to be developed as a result of the research efforts.

CHP plants and integration of renewable electricity (Improved sector interaction)

CHP plants should be operated in such a way that they produce less when the renewable electricity production input is high and more when the input is low. When including heat storage capacity, this is likely to help integrate fluctuating renewable electricity of up to 20-25 per cent of the demand without sacrificing fuel efficiency in the overall system. After this point, system efficiency will decrease as heat production from CHP plants is replaced by thermal or electric boilers. Further research is needed to enhance the interaction and integration with large-scale heat pumps in CHP plants and district heating systems.

Liquid fuel produced from the electricity and the gas sectors (Improved sector interaction)

A crucial element in the cross-cutting interaction between the sectors is the large-scale development of liquid transport fuels which will replace fossil fuels such as electrofuels. This will require heavy integration and interaction between the electricity sector and the gas sector in order to create efficient production and meet constant demand.

Although steps are being taken to bring HTL into the demonstration scale for transport fuel production, there is still significant research to be carried out to fully realise the potential of HTL. Additional to this step which involves scaling not only of the process, but also of the investments needed, this includes studies on suitable feedstocks, co-processing of these, product and process optimization, and exploration of synergies with other processes and systems. Catalytic processing both in the primary HTL conversion step as well as for hydrotreating and potential integration into existing refinery processes [233,234] is another priority.

7. Non-technical (Social, socio-economic and political dimension)

In this section, the state-of-the-art research for the societal sector in Smart Energy is described. *Table 10* below presents a brief overview of the main topics in the state-of-the-art research. The main research gaps are also presented in *Table 10*. Although some areas are currently being researched, research gaps may occur in the areas; thus, they are included in both columns in the table.

Table 10: Summary of key areas included in state-of-the-art Smart societal research, and research gaps

State-of-the-art topics	**Main research gaps**
Focus on institutions and organisations	Focus on institutions and organisations
Electricity markets and market design	Electricity markets and market design
User participation and interaction	Ownership projects
	User participation and interaction
	Export potential for grids, infrastructures and technologies

A detailed description of the state-of-the-art research in the societal sector is presented below, beginning with a summary.

Summary of the state-of-the-art

The research under this theme is concerned with the development and implementation of smart energy systems from a non-technical perspective. This entails analyses of how smart energy systems should be supported politically, economically and socially, and which kinds of institutional and organizational changes and learning processes are required in order to do so. The research theme is therefore strongly linked to and rooted in (Socio-Economic) Innovative Feasibility Studies and the development of Strategic Energy Planning (in Danish municipalities). The research themes proposed below are seen as concrete sets of tools and topics that support the further development of Feasibility Studies and Strategic Energy Planning linked to smart energy systems.

Three overall research themes are proposed:

1. Policies for coordination, institutional innovation and smart energy systems
2. Local ownership and local initiatives for the development of smart energy systems
3. Learning processes for the development of smart energy systems

7.1. Policies for coordination, institutional innovation and smart energy systems

The technological change of the energy system entails increased amounts of fluctuating supply. This change creates a need for institutional reforms in order to obtain a resource efficient cross-cutting integration of all energy sectors. From technical system analyses, it is known that a 100 percent renewable energy system would need to allocate the fluctuating supply across all energy sectors [235]. Wind and solar energy would need not only to be coordinated with electricity sector end use, but also with flexible conversion units such as heat pumps and electrolysers [38,236]. In such systems, fluctuating supply thus has to be allocated through both time and space. The technological change gives rise to institutional challenges where a lot of independent economic actors would have to be coordinated according to the exogenously given fluctuating supply. This development would require institutional innovation where alternative organisational concepts are developed and implemented.

Institutional challenge integrating electricity and heat (Focus on institutions and organisations)

The first-coming institutional challenge in the technological change is happening in the area of integrating heat and electricity sectors. Geographically, Denmark is an interesting research area in the coming years as a consequence of a high RE share in the electricity production combined with a well-established district heating sector [237,238]. This country therefore has the basic technological prerequisites for advancing to the next step of a smart energy system development. Previous research has shown that installing large-scale heat pumps in the Danish district heating sector could improve the system ability to integrate growing amounts of fluctuating wind power productions [38,236,239]. Likewise, technical system analyses indicate that natural gas based CHP is well suited as back up capacity for fluctuating renewable resources in the electricity sector, and thereby offers system benefits which are not reflected in the short-term marginal production costs. While the development in the Danish energy system so far has succeeded in increasing the wind power capacity, the system capacity to integrate wind power has not developed with the same pace. Empirical data shows that large-scale heat pumps have not been installed in any significant amounts. Likewise, natural gas based CHP is under economic pressure in the Nord Pool spot market since this production form is crowded out by the increasing amounts of wind power. Meanwhile, increased uses of biomass in electricity and heat productions is a problem since biomass resources would have higher alternative value in a future transport system [237,240]. Institutional structures should therefore minimise biomass consumption in heat and electricity sectors.

The resource inefficient development is a result of a malfunctioning institutional structure that does not sustain the flexible and efficient integration of heat and electricity markets, which is a vital next step in the development of the smart energy system. The current tax structure in Denmark does not deliver the required incentive structure neither at the investment nor operation level. Future research should investigate various institutional models that could ensure the resource efficient integration between heat and electricity markets.

The institutional models should address both investment decisions and subsequently daily operation decisions. Incentives should guide economic actors towards not only establishing the necessary infrastructure but also ensuring a flexible operation of the individual parts in order to match the fluctuating supply. Specifically for the Danish power-to-heat challenge, investment decisions are a complex process influenced not only by consumer and business economic considerations, but also socioeconomic evaluation procedures – as it is required by the Heat Supply Act regulation [241,242]. Elements of such evaluation procedures have so far been treated critically at a theoretical level, as it has been the case of, e.g., the concept of tax distortion loss and cost benefit analysis methodologies [243–245]. However, it is important to understand how the mix of different theoretical concepts adds up and structurally affects allocation in its specific uses. This has so far not been carefully analysed for the Danish energy sector. It is important to make inquiries into the socioeconomic evaluation procedures and understand these as part of the institutional structure. Since such procedures have a direct effect on investment decisions, they may act as an institutional barrier, or support, to the development of a smart energy system. Further, system benefits and costs which are not valued in current markets may have to be more systematically included in socioeconomic evaluation procedures. Updating and adjusting socioeconomic methodologies to the new technological paradigm make an important research area for the years to come.

Some tentative research question examples

1. Which institutional reforms may promote a resource efficient integration of heat and electricity sectors?
2. Which institutional models can promote a resource efficient integration of all energy sectors?
3. How can processes of economic investment decisions be understood?
4. How are theoretical concepts translated into concrete socioeconomic evaluation procedures, and how do they work as part of the institutional structure?
5. How can socioeconomic methodologies be developed in order to support a smart energy system?

7.2. Local ownership and local initiatives for the development of smart energy systems

The transition towards a smart energy system, based on efficient end-use of energy and a 100% renewable energy supply, will to a great extent be based on existing and new local and regional infrastructures, including (onshore) wind power, district heating, energy-efficient building solutions, clean vehicles and transport solutions, biomass production and biofuels, gas grids as well as photovoltaic systems – to name some important examples [38]. This means that citizens and other local actors to an increasing extent will be affected by and also participate in the transition towards a smart energy system in various ways. Municipalities, for instance, have been identified as key actors in the strategic energy planning of 100% renewable energy systems by the Danish Energy Agency [246–248]. However, this transition should not come at an unnecessarily high cost to local actors and society as a whole. At the same time, there is the risk that local communities in many places may find themselves exposed to new energy infrastructures which may have negative impacts locally and may therefore generate opposition towards the renewable energy transition. In addition to that, these places, even though rich in renewable energy sources such as wind, solar and biomass, may struggle with structural problems such as unemployment, decreasing population and eroding infrastructures. It is therefore of the utmost importance that local communities participate actively in the implementation of smart energy system solutions, in order to generate support for the renewable energy transition and simultaneously solve the challenges of local and regional development.

With its long history of locally organised and initiated energy projects, including wind power, CHP and district heating as well as biogas, Denmark is an excellent starting point for the research on the next phases of these kinds of local initiatives in the light of smart energy systems. This research theme builds to a large extent on the practical experiences with local and regional energy development gained in Denmark and elsewhere across Europe [249–252], and opens up a new field of research linking smart energy systems with local and regional development. The research under this theme deals with the possibilities and problems associated with smart energy system developments at the local and regional level. In particular, the theme is concerned with the question of how the development of smart energy systems can improve the development possibilities of local citizens, local communities, and local businesses as well as local and regional authorities. Conversely, the theme investigates the (changing) roles of these actors in smart energy system developments. This includes an investigation of adequate ownership and investment models that both accelerate the implementation of smart energy system solutions and improve the local and regional economy. Such research can be linked to wider feasibility studies and socioeconomic analyses, in the sense that supporting local development through smart energy systems should also generate benefits at the central level for the state and society as a whole [253,254].

New market schemes encouraging end-users to participate in 100% renewables (Electricity markets and market design)

Generally, there are two adverse consequences in future wind dominant electricity markets: the overmuch price reduction and high price volatility. While high price volatility imposes elevated risk levels for both electricity suppliers and consumers, an excessive price reduction of electricity is a disincentive for investment in new generation capacity and might jeopardize system adequacy in the long term [255] indicates that the discriminatory pricing approach can be beneficial in high penetration of wind power because it alleviates high price variations and spikiness on one hand and prevents overmuch price reduction in wind dominant electricity markets on the other.

But only improving the bidding and clearing strategies in the electricity market is far from enough. In 2014, a single one-day-ahead clearing market has been built up covering 15 countries and 75% of the electricity consumption in Europe. Meanwhile, the European Commission will gradually downsize the subsidy to renewable energy. From the power plant owner's point, the uniformed market and downsizing of the subsidy have enhanced the competition within the energy sector, which encourages the resource optimization across the nation and even across energy systems.

From the system operators' point, the consumers are not as actively participating as expected. At the same time, the intermittent renewable sources are not so dispatchable. So further research on market schemes is needed to make use of the cross-border interconnections more efficiently and further improve the social welfare.

Aggregation of flexible demand (User participation and interaction)

Demand-side management is often promoted as one of the strategies by which balance can be ensured between demand and supply in an energy system based on increasing shares of intermittent electricity. The demand-side of the energy system, however, consists of many small end-users with relatively limited levels of demand flexibility, and with relatively limited economic incentives. Often it is too inconvenient and costly for these small-scale end-users to, e.g., sell their end-use flexibility to the electricity market on an individual basis.

It may therefore be necessary to aggregate the demand flexibility of many individual end-users, in order to make this flexibility operational in balancing the grid.

3rd party aggregators signify companies or 'roles' within companies that are specialised in harvesting and pooling the demand flexibility of many small-scale end-users in order to sell this flexibility on the electricity markets. 3rd Party aggregators harvest and pool flexibility through contracts with end-users that allow the aggregator some level of control over the end-users' flexible consumption devices – e.g., domestic heat pumps, electric vehicles, or supermarket cooling systems.

3rd party aggregators can sell the demand flexibility on two energy markets: (1) the spot market (day ahead market, intra-day market) or (2) on the regulating power market. These markets are operated by the TSO (in the Danish case energinet.dk) and bids can only be placed by balancing responsible parties (BRP) that have signed an 'agreement on balancing responsibility' with the TSO. The 3rd party aggregator must therefore sell his flexibility to an established BRP or apply to become a BRP himself.

In the day ahead spot market (the largest spot market), the BRPs place bids on both consumption and production for each hour of the following day at the prices and volumes that they are willing to trade. This auction closes at 12 o'clock and hourly prices are settled at the intersection between aggregated supply and demand [256].

Current market rules, however, prescribe that the consumption settlement in the energy markets for small end-users (below 100,000 kWh/year) follows the 'load settlement method'. This is a settlement method by which energy consumption is only measured once a year. There is no registration of hourly consumption of the individual end-user, and flexibility therefore cannot be traded at the energy markets. Hourly settlement of electricity consumption – based on hourly metering of consumption - only applies to end-users with an electricity consumption above 100,000 kWh/year [256]. Smart meters are, however, expected to be rolled out to all end-users by 2020. This opens opportunity for trading the flexibility of small end-users.

At the balancing power market, imbalances in the spot market settlements of the BRPs are traded 45 min before delivery hour, in order to balance the system. BRPs place bids for upward or downward regulation. According to market rules, the minimum bid volume is 10 MW, and the BRP must be able to activate the full delivery within 15 min. It is allowed to make a regulation bid by aggregating a portfolio of consumption units. The aggregation of flexible demand in the balancing power market, however, requires that the flexible energy consumption of the end-user is separated from the traditional non-flexible energy consumption. To this end, market rules require that separate meters are installed for the flexible consumption units in order to allow for hourly metering (on-off cost between 10,000-50,000 DKK and running costs around 2000 DKK/year) [256].

There are considerable costs associated with establishing a 3rd party aggregator business. The business set-up of an aggregator requires functions such as: marketing, sale, analysis, installation, forecast, planning, optimisation, trading, market interfaces, and competent staff.

Previous analyses argue that the business case may be improved by introducing less costly market rules. This could include that the requirement for online metering on single devices in the regulating power market is replaced by statistical tools, that standard agreements are developed between BRPs and 3rd party aggregators, and that the minimum bid in the regulating power market is lowered. It should be noted that the question of whether market institutions are able to promote 3rd Party aggregation is also debated at the EU level (see e.g. [257])

Danish research in relation to 3rd party aggregation is limited. Within the I-power project, there has been some research into how to operationalize aggregation services. This research has, e.g., developed algorithms (a so-called virtual power plant) on how to aggregate the individual demand flexibility from supermarket refrigeration systems [258] and domestic heat pumps [259].

Electricity markets (Electricity markets and market design)

In recent years, more than 400 MW of electrical boilers have been installed at Danish district heating companies. These electrical boilers have already today become important examples of Smart Grid components for integrating fluctuating productions from wind turbines and photo voltaic.

In a socioeconomically feasible way, most of these electrical boilers have been connected to the electrical grid without having paid for reinforcements of the grid – but as a consequence these electrical boilers are only allowed to use the instantaneous net reserve. This instantaneous net reserve is typically communicated from the distribution grid operator (DSO) every 5 minutes to the district heating companies.

But the market driven use of the instantaneous net reserves in a Smart Grid causes problems, due to gate closures in the different electricity markets at the TSO level. As an example, when a district heating company makes a bid at 12 o´clock the day before in the day ahead spot market for purchasing electricity to its electrical boiler, the district heating company in fact does not know if, when coming to the operating hour, there will be sufficient net reserve for consuming the purchased electricity. That may eventually end up with a punishment for imbalance, if the district heating company does not consume the purchased electricity.

This case is a challenging example of Smart Grid operation. If, e.g., the prices become sufficiently negative in the regulating power market, both the wind turbines and the electrical boiler will win downward regulation and as a result, the wind turbines stop and the electrical boiler is turned on – or said in another way – the energy that flows through the transformer will, within a few minutes, change direction.

Since the electrical boiler is only allowed to use the instantaneous net reserve, this may also influence its ability to participate in the regulating power market.

5s' [260] is a research project supported by the Innovation Fund Denmark, which will be focusing on what future electricity markets may look like, when reaching a high penetration (>50%) of renewable energy sources, with new consumption patterns and increased coupling with neighbouring power systems. It is of utmost importance to rethink the way in which electricity is exchanged and priced through markets. Future electricity markets must be able to optimally deal with the dynamics and uncertainties of renewable energy generation, as well as with dynamic and flexible offers on the demand side. They should fairly re-distribute the increase in social welfare while providing enough returns to electricity producers for them to make appropriate investments. It is the core objective of the '5s' project to forge the scientific and technical core for such future electricity markets to become a reality. This will be in order for the Danish power systems (and others to follow) to have the proper market mechanisms to cope with 50% (and more) renewable energy in the power systems. In that objective, the '5s' project will propose new market mechanisms in an advanced optimization framework, from the base methodological developments to the practicalities of their implementation requiring a parallel computing environment.

In [261] about integrating renewables in electricity markets, the book addresses the analytics of the operations of electric energy systems with increasing penetration of stochastic renewable production facilities, such as wind- and solar-based generation units. As stochastic renewable production units become ubiquitous throughout electric energy systems, an increasing level of flexible backup provided by non-stochastic units and other system agents is needed if supply security and quality are to be maintained. This book also describes the use of probabilistic forecasting in online optimization approaches.

Ancillary services and centralized and decentralized control (Electricity markets and market design)

Though efforts have been devoted, the major issue still remains that the ancillary services provided by the distribution systems cannot be quantified. So the profit and revenue cannot be calculated to award the distribution system operators and encourage them to actively participate.

Another challenge is the trade-off between centralized and decentralized control. The former one needs considerable investment in communication infrastructures and at the same make full use of all the controllabilities of different devices instantaneously. Comprehensive analysis and optimization are needed for this topic.

Dispatchable power plants (Electricity markets and market design)

Many power plants including CHP units are experiencing feasibility challenges due to decreasing income from wholesale markets. This can, for example, be seen in the significant decrease in capacity of large coal-fired CHP units in Denmark. Dispatchable capacity will still be needed in future smart energy systems based on variable RES, in order to have production capacity during periods with little or no production from variable RES. For this reason, an ongoing discussion takes place regarding how to ensure sufficient capacity of flexible dispatchable units, for example in both Denmark [262] and Germany [263]. Many different proposals are being discussed; however, it is still unclear how market-based smart energy systems can be organised in order to facilitate variable RES, while also ensuring sufficient capacity of efficient flexible dispatchable units.

Gas regulatory framework (Focus on institutions and organisations)

Research in the role of the role of gas grids in future smart energy systems from a technical side needs to be supported by research into maintaining an efficient and long-term ownership structure. Development of the regulatory framework that will support these technologies is essential.

Some tentative research question examples

1. Which are the concrete possibilities for local actors to initiate and actively participate in the implementation of smart energy system solutions?
2. How should one conceptualise local and regional development/economy in the light of the transition towards a smart energy system?
3. Which are the concrete (local) economic effects that these smart energy system solutions can have in terms of the above conceptualisation(s)?
4. Which kinds of (local) ownership and business models can improve local and regional development and generate community support for smart energy system solutions?
5. How should these ownership and business models be supported at the local, regional and central levels?

7.3. Learning processes for the development of smart energy systems

The change from fossil fuel technologies to energy conservation and 100% renewable energy is a development from sectoral energy supply technologies to smart energy systems where the increasingly large share of fluctuating renewable energy is utilized efficiently by integrating heat and power markets, biomass and the production of synthetic fuels, and by introducing electrical transport, etc. All of it coordinated with systematic energy conservation activities in such a way that it ensures the right size and technological composition of the supply side technologies.

Thus, there is an increasing requirement for concrete collaboration and coordination procedures between the state level, municipalities, producers and owners of renewable energy plants, consumers and producers of heat, biomass and power, and also in a learning process of the democratic base, the households.

We are therefore dealing with a technological transition that implicates and requires a profound learning process both at the central political and administrative level, at the local and regional level of technological development, and at the basic household level.

The conceptualization of households

Until now, a relatively limited success with integrating households in the smart energy system raises the question whether the previous approaches to households have been relevant. Danish and international studies of Smart Grid demonstration projects indicate a need for a more nuanced understanding of the consumers (households) and their possible future role in the smart energy system.

Among designers and planners of Smart Grid and smart energy solutions, there is a widespread conceptualization of the consumers as demonstrating “rational behaviour” in relation to their energy consumption. This understanding typically emphasizes the role of economic incentives (e.g., price signals) as a main driver of the active involvement of households in smart energy solutions (e.g., DSM). Sociological studies problematize this one-sided understanding of consumers. While not disregarding that economic incentives do play a role, this research field points to the need for a much broader and more contextualized understanding of the consumers and the user context (e.g. [264–266]). It is necessary to understand energy consumption as an integrated part of the daily activities of household members; it is the outcome of the multiplicity of meaningful daily practices that people are engaged in such as cooking, showering, entertainment, hobbies, etc. In this way, it is difficult to address energy consumption in isolation from the context in which this happens. Thus, this research field contributes with new and more complex insights into the potentials, limitations and challenges of introducing new smart energy technologies and solutions for households. Also, the studies of the user context can, if better integrated into the design of new technical solutions and services, contribute to the design of more “robust” and effective solutions. Statistical models are useful to describe the possibly aggregated user response.

Inter-organizational and interdisciplinary learning processes

Inter-organizational and interdisciplinary learning processes have so far not sufficiently been dealt with from a research point of view. It is in many of its aspects a new research area within the energy field.

It is of profound importance systematically to develop principles[267] for the design and implementation of this inter-organizational and interdisciplinary learning process, as an equal research theme synchronized with the development of smart energy system scenarios.

To develop and implement these principles is a very difficult task, as it deals with establishing useful collaboration between organizations and people with different traditions, different professional knowledge, different organizational goals, and different resources[268,269].

For instance, a constructive learning process must be established between the ministries of finance, taxation and energy, which does not seem to be in existence today where changes of the tax system are not coordinated with the goals of energy policy[195]. There is also a need for a mutual learning dialogue between the economists and political scientists at the central administrative level, the planners at the municipal level, and the engineers in energy companies and at universities[38]. This dialogue process is not functioning well today.

And the most important feature; there has to be a learning dialogue between technocrats and planners at all levels and local and regional NGOs and normal households, developing a basic understanding at the citizen level regarding the change from fossil fuel sectoral systems to fluctuating renewable smart energy systems.

As a consequence of the above discussion, there is a need for research within the following areas:

Some tentative research question examples:

1. How can a learning procedure be implemented that establishes a better interaction between policy development and coordination at the central administrative level and policy conditions at the regional and decentral level?
2. How can a better interdisciplinary communication between engineering and social science knowledge be established between actors at different levels?
3. How can a dialogue between planners and households at the decentralised level be designed so that it sufficiently benefits from ideas and initiatives at the household level?
4. How can a learning process between schools, universities, municipalities and local and regional companies within the energy area be established?
5. How can a process be established where the knowledge at the local and regional level is transferred to the central political and administrative level [270,271]?
6. In general; how should organizations that can establish the learning interactions in points 1-5 look like? How should they concretely work? Which resources would they need?

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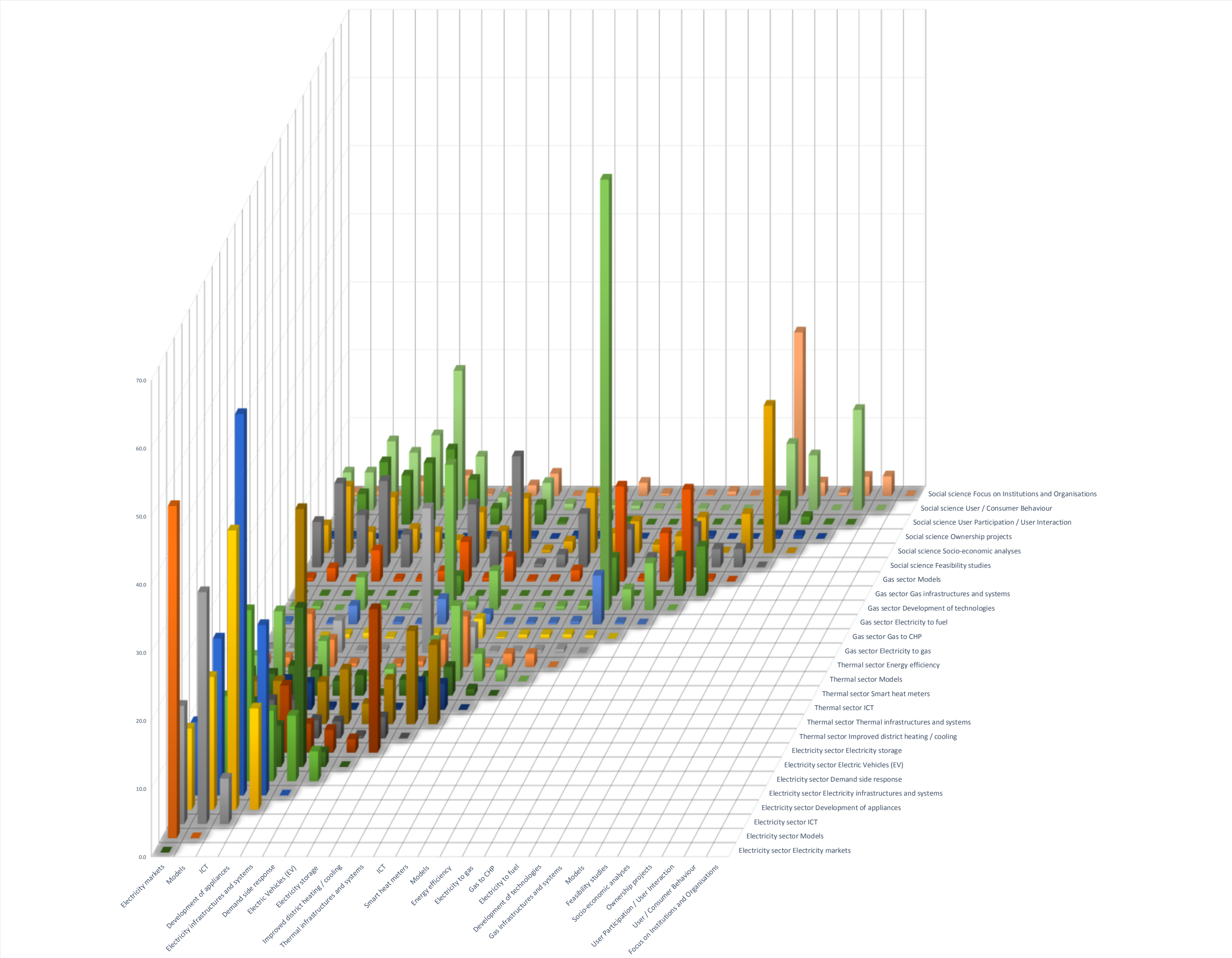
Appendix A – Danish project results

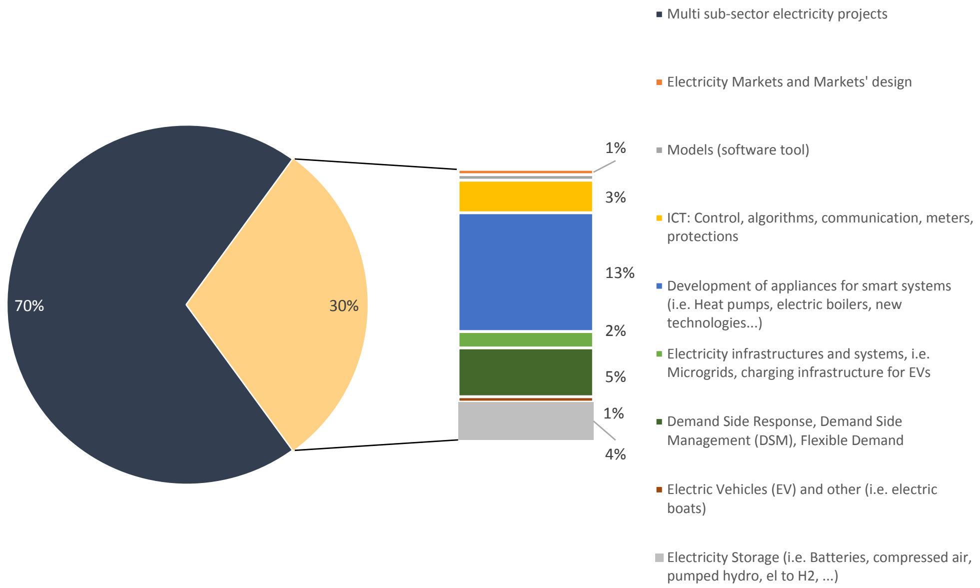
The figure and the table below provides a complete picture of the budget allocation between all the energy sub-sectors. The results illustrate the total budget for combinations of one sub-sector with other sub-sectors.



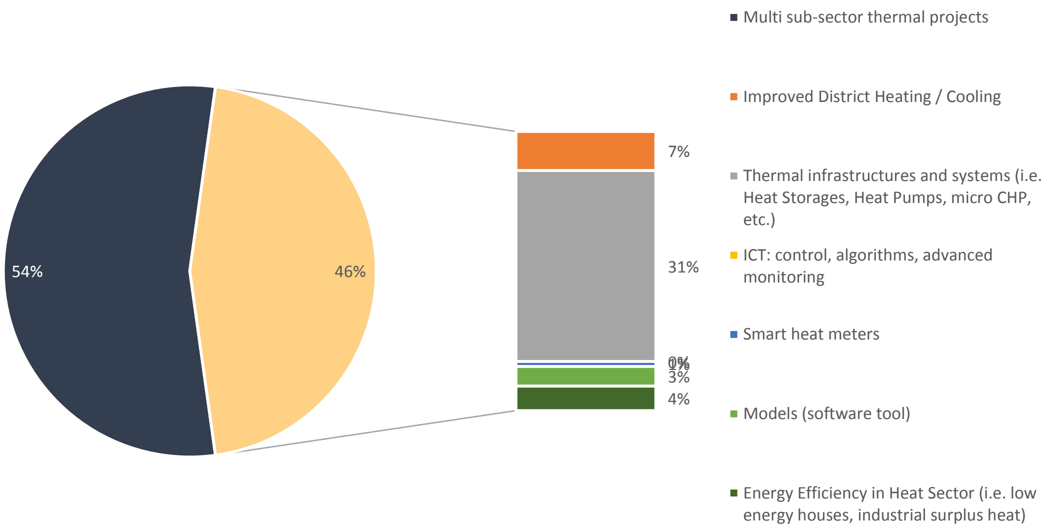
		Electricity sector								Thermal sector						Gas sector						Social science					
Electricity sector	Electricity markets	0.0																									
	Models	48.8	0.0																								
	ICT	17.4	34.1	6.7																							
	Development of appliances	11.9	19.5	41.0	14.9																						
	Electricity infrastructures and systems	10.8	23.1	56.0	25.0	0.0																					
	Demand side response	10.1	12.5	25.1	10.3	9.6	4.4																				
	Electric Vehicles (EV)	4.7	6.5	9.5	6.0	23.4	2.2	0.0																			
	Electricity storage	6.0	7.0	5.3	9.9	4.2	3.4	2.0	21.1																		
Thermal sector	Improved district heating / cooling	3.2	3.3	5.7	5.7	2.7	2.5	0.4	3.1	0.0																	
	Thermal infrastructures and systems	5.7	6.3	6.3	31.6	6.2	8.0	3.0	6.5	13.7	11.6																
	ICT	0.4	0.4	4.4	4.0	0.4	0.2	0.2	0.2	4.1	3.9	0.0															
	Smart heat meters	3.6	3.2	4.4	3.8	2.2	3.0	0.2	2.3	2.8	4.2	0.9	0.0														
	Models	3.8	10.3	2.0	5.9	0.5	0.8	1.8	1.7	6.0	11.1	4.1	1.7	0.0													
	Energy efficiency	1.2	1.4	7.8	4.0	0.5	8.2	0.5	0.8	4.0	7.5	0.5	2.0	2.0	0.0												
Gas sector	Electricity to gas	0.6	0.7	0.2	4.7	0.3	0.5	0.2	21.2	0.8	3.8	0.2	0.2	0.4	0.5	0.0											
	Gas to CHP	0.8	0.8	0.2	0.6	0.8	0.2	0.0	0.8	1.4	2.9	0.2	0.6	0.6	0.6	0.4	0.0										
	Electricity to fuel	0.4	0.5	0.2	2.7	0.3	0.3	0.2	3.7	0.4	1.5	0.2	0.3	0.3	0.4	7.2	0.2	0.0									
	Development of technologies	0.5	0.6	0.0	4.8	0.7	0.2	0.1	21.4	1.3	5.7	0.0	0.4	0.5	0.6	63.2	3.1	6.9	0.0								
	Gas infrastructures and systems	0.0	0.1	0.0	0.0	0.0	0.0	0.1	2.9	0.0	0.1	0.0	0.0	0.0	0.0	5.6	0.0	0.0	5.8	7.3							
	Models	0.5	2.0	0.2	4.6	0.3	0.3	1.5	5.8	0.5	3.6	0.2	0.2	1.7	0.4	14.0	0.4	7.1	13.5	0.4	0.0						
Social science	Feasibility studies	6.7	12.3	7.7	12.7	4.8	6.2	1.8	9.2	4.5	16.3	0.5	1.9	7.9	4.3	5.6	1.4	0.7	6.0	2.7	2.7	0.0					
	Socio-economic analyses	4.1	9.8	3.1	8.2	3.6	3.1	1.9	6.0	3.2	8.0	0.4	1.7	8.8	2.9	4.7	1.2	2.4	5.2	0.1	5.7	21.6	0.0				
	Ownership projects	0.4	0.4	0.0	0.5	0.0	0.0	0.0	0.4	0.5	0.4	0.0	0.4	0.4	0.5	0.1	0.4	0.0	0.4	0.0	0.0	0.5	0.5	0.0			
	User Participation / User Interaction	3.2	4.5	9.2	7.2	9.0	11.0	6.6	2.4	0.6	2.9	0.3	0.7	1.3	0.4	0.0	0.0	0.0	0.1	0.0	0.0	4.2	1.1	0.1	0.0		
	User / Consumer Behaviour	5.6	5.6	10.1	8.5	11.0	20.5	7.9	1.9	0.6	4.0	0.9	1.0	0.7	0.6	0.2	0.2	0.2	0.0	0.0	0.2	9.8	8.1	0.0	14.7	0.0	
	Focus on Institutions and Organisations	0.5	0.6	0.0	2.2	0.4	3.0	0.3	0.6	1.6	3.3	0.0	0.4	0.6	1.9	0.3	0.4	0.2	0.6	0.0	0.1	24.0	2.0	0.5	2.8	0.0	0.0
		Electricity markets	Models	ICT	Development of appliances	Electricity infrastructures and systems	Demand side response	Electric Vehicles (EV)	Electricity storage	Improved district heating / cooling	Thermal infrastructures and systems	ICT	Smart heat meters	Models	Energy efficiency	Electricity to gas	Gas to CHP	Electricity to fuel	Development of technologies	Gas infrastructures and systems	Models	Feasibility studies	Socio-economic analyses	Ownership projects	User Participation / User Interaction	User / Consumer Behaviour	Focus on Institutions and Organisations

The figures below show the number of times (in percentage) that a sub-sector of each energy sector is focused on in all single sector projects. A project may focus on more than one sub-sector but each time a sub-sector is focused on it is counted in the figure.

The figure below presents the proportion of occasions on which a sub-sector is researched in all single sector electricity projects



The figure below presents the proportion of occasions on which a sub-sector is researched in all single sector thermal projects



The figure below presents the proportion of occasions on which a sub-sector is researched in all single sector gas projects

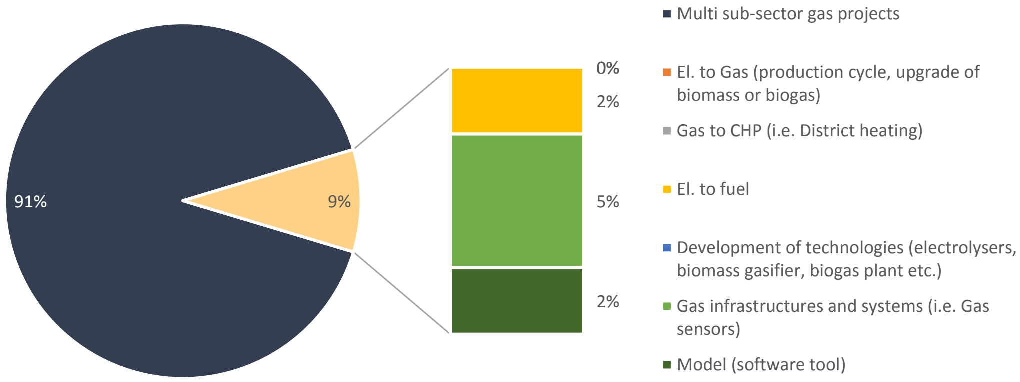
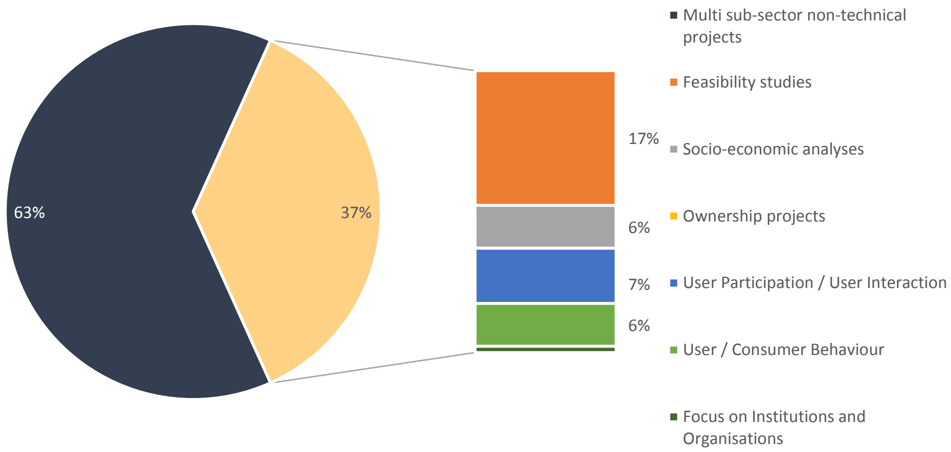


Figure 45 below presents the proportion of occasions on which a sub-sector is researched in all single sector non-technical projects



Appendix B – Selected Danish projects

This appendix provides a list of the 225 Danish projects selected after the screening for the present study. Projects are listed in alphabetical order.

Danish projects selected for the study in alphabetical order.

Project name
4DH - Strategic Research Centre for 4th Generation District Heating Technologies and Systems
Agent-based control structures in power systems with considerable decentralized production
Aluminium phase transition energy storage
Anayse af varmpumpe til varmeforsyning med fjernvarmereturen
Application of Smart Grid in photovoltaic power systems
Application of Synchronous Condensers
Auxiliary Hybrid Power
Biogas for transport
Biogas SOEC
Bolig+ - realisering af energineutral boligbebyggelse
Bolig+ måling, evaluering og formidling
Boligejendomme med CO2 neutralt elforbrug - fase 1
Boreholes in Brædstrup
Boreholes in Brædstrup - supplementary grant
Borgernær indsats til fremme af SEP i yderområderne
BPES - Balancing power energy system
Bæredygtig energiforsyning af Nye - den nye by ved elev i Aarhus
Bæredygtige energi-plus huse - part 2 SDE2014
CanDan1.5 - Analysis of power balancing with fuel cells and hydrogen production plants
CEEH - Centre of Energy, Environment and Health
CEESA - Coherent energy and environmental system analysis
Changing the heating market mechanisms: Boiler information system on efficiency - BISON Project
ChooseCOM - Large-scale demonstration of charging of electric vehicles (test en elbil)
CHPCOM Combined Heat and Power Communication
CITIES - Centre for IT-Intelligent Energy Systems in Cities
COMETS - Co-Management of Energy and Transport Systems
Consumer acceptance of intelligent charging
Control and regulation of modern distribution system
Coordicy
CORPE: Center Of Reliable Power Electronics
Dansk deltagelse i IEA EBC Annex 67 Energy Flexible Buildings
Decentralized biogas plant with heat pumps, heat storage and automation
Deltagelse i IEA ESES Annex 31 Energilagring til bygninger og områder
Demand response medium-sized industry consumers
Demonstration af strategisk energiplanlægning på Bornholm som afgrænset ø-samfund (Bright Green Island)
Den intelligente gasmåler
Development and demonstration of IR gas sensor
Development of a secure, economic and environmentally-friendly modern power system
Development of SOEC cells and stacks
District energy innovation lab
DREAM - Danish Renewable Energy Aligned Markets - Phase 1
DSO challenges from introduction of heat pumps

Dynamic Allocation of Power to EVs
Dynamic topology data in distribution grids
Dynamisk allokering af el til el-biler
EBC - Annex 64: "LAvX Samfund
ebutler - effektivisering af energiforbrug
EcoGrid.dk
EDGE - Efficient Distribution of Green Energy
EDISON consortium: Consortium for Electric vehicles in a Distributed and Integrated market using Sustainable energy and Open Network
Efficient conversion of renewable energy using solid oxide cells
Efficient incorporation of wind power in district heating systems
eFlex
El til vejtransport, fleksible elsystemer og vindkraft
El upgraded biogas
ELECTRA top up financing (EERA Smart Grid Integrated research project)
Electricity demand and frequency controlled reserve - implementation and practical demonstration
Electricity storage for short-term power system service
Electrogas - The renewable e-power buffer
Energi på Tværs
Energibesparelser via spændingsregulering
Energibyg: klima og energieffektivt byggeri
Energieffektiv mælkekøling med intelligent styring
Energilager til supermarkedskøleanlæg
Energiplan Fyn
Energy city Frederikshavn: 100% renewable energy
Energy forecast
Energy Storage - Hydrogen injected into the Gas Grid via electrolysis field test
Energyflexhouse family: Intelligente energiydelser baseret på brugerdrevet innovation
EnergyLab Nordhavn - New Urban Energy Infrastructure
EnergyLab Nordhavn - Platform for development of smart city energy solutions
ENSYMORA - Energy systems modelling, research and analysis
e-STORE: Further improvement of PEM electrolysis for flexible energy storage
Et Energisk Nordjylland
Etablering af lavtemperaturfjernvarme i eksisterende varmeforsyning
EUDP- 13-l, optimering af grundvandsvarmepumper
EUDP13-I, Hybrid heat pump for district heating
EVergreen - intelligent charging of electrical vehicles
Fjernkøling light
Fjernvarmedrevne absorptionsvarmepumper med jordlager til bygninger fase 1
Fjernvarmeunit med elpatron til ultra-lavtemperaturfjernvarme
Flexcom - communication requirements for flexible control of distributed power systems (IEC 61850 and IEC 61970)
Flexgas - fleksiblet energiforbrug med elpatron i villagaskedel
FlexPower - perspectives of dynamic power prices
Fra plusenergihus til plusenergiområde
Fra storehus til solhus
Fremtidens fjernvarme. Litteraturstudie
Fremtidssikring af dansk produktion af varmepumper, Hovedprojekt
Fremtidsstrategier for mindre fjernvarmesystemer - fase 1
Generic virtual power plant (VPP) for optimised micro CHP operation and integration
Green Flex – Mobilizing Operational Flexibility in Green Energy Production

Green Gas Test Center (Testcenter for grønne gasser)
Green Lab for Energy Efficient Buildings - GLEEB
Green natural gas
Green Power Electronics Test- PhD Project (Green PET-PhD)
GreenCom Top-UP
GreenSynFuel
GRENAA – energiforsyningsstrategi 2014
Grundvandsvarmepumper og - køling med grundvandsmagasiner som sæsonlager
Grøn ”least-cost” energihandlingsplan for Billund Kommune
Handlingsplaner om øget fleksibilitet i lokale energisystemer
HIGHE
Holiday residences and Smart Grid - a plug 'n' play-concept
Høje-Taastrup Going Green
Højtemperatur varmepumper kan bruge lavtemperatur spildvarme
Håndtering af demand-response kapaciteten fra erhvervsbygninger
iDClab - Intelligent DC Microgrid Living Lab
IDE4L-DK Top-up
IEA Heat Pump Program EXCO participation as ‘representative member’
IEA HPP Annex 42 ”Heat Pumps in Smart Energy Grids for Sustainable Cities”
IEA HPP Annex 42 ”Varmepumper i Smarte Energi netværk til bæredygtige byer”
IEA Task 42, Compact Thermal Energy Storage - 4. year of participation
IEA-DHC Annex X: 4th generation district heating
IMPROSUME: The impact of prosumers in a Smart Grid based energy market
INCAP - Inducing consumer adoption of automated reaction technology for dynamic power pricing tariffs
Increased output of WTE by use of heat pumps
Increasing energy system flexibility and efficiency by using heat pumps in CHP stations
Industrielle varmepumper - IEA
Information and education of the future power consumer
Integration of Renewable Energies by distributed Energy Storage System
Integrering af husholdninger i det smarte elnet (IHSMAG)
Intelligent remote control for heat pumps
Interactive meters for activation of price elastic power consumption
IPOWER - strategic platform for innovation and research in intelligent power
Kombineret fjernvarmeforsyning af lokalområde
Konkurrencedygtige fjernvarmetariffer
Køleplan Danmark
Landsbyvarme med varmepumper og ATES
Lavressource fjernvarme
Lavtemperaturfjernvarme i eksisterende bebyggelser
Lavtemperaturfjernvarme der ikke giver legionella-problemer
Livø - First implementation of energy supply options
Livø - Further implementation of energy supply opt
Local Energy Storage
Manual power reserves from telesites
Marina power distribution hub with Smart Grid functionality
MeGa-Store - Methane gas for storage of VE
MeGa-Store, Optimization and scale-up
Merindtjening til kraftvarmeværker ved hjælp af systemydelser
Micro-grid Technology, Research and Demonstration
Midt Energistrategi
Modeller i EU-projektet stoRE af økonomien i ellagre

NEMO - Novel E-MObility Grid Model (A)
NEMO - Novel E-MObility Grid Model (B)
NEMO - Novel E-MObility Grid Model (C)
Nikola - Intelligent Electric Vehicle Integration
Ny CO2 neutral bydel i Høje Taastrup
Ny metode til overvågning af strømforbrug
Ny standard for fjernvarme til lavenergibyggeri
Nyt værktøj til analyse af hybride forsyningsanlæg til større bygninger
Off peaking af elforbrug til el-opvarmede energilagre
Omkostningseffektiv, online varmepumpe
Omlægning af husholdningers elforbrug til fjernvarme: tørretumblere, vaske- og opvaskemaskiner
Optimal udnyttelse af solcelle et i énfamiliehus
Osmotic Power generation from geothermal wells
PlanSOEC
Power2Hydrogen
PowerLabDK
PowerLabDK (Real time demonstration test and evaluation of Bornholm electricity network with high wind power penetration)
Power-to-gas via Biological Catalysis (P2G-BioCat)
Price elastic power consumption and power production in the industry
Price elastic power consumption as reserve power - a demonstration project in the gardening sector
Proactive participation of wind turbines in the electricity markets
PROAIN - PROActive INtegration of sustainable energy resources enabling active distribution networks
Professionelle energi-fleksible vaskemaskiner til Smart Grids
Project Zero Sønderborg
På vej mod en renere energiforsyning
READY - Smart Grid ready VPP controller til varmepumper
ReLiable - Reversible Lithium-Air Batteries
Remote services for CHP
Renewable energy storage for the future
Roadmap for fjernvarmen - fjernvarmens rolle i energisystemet
RTLabOS: Phase I
SAVE-E
SDVP2 Styr din varmepumpe version 2
Self-organising distributed control of a distributed energy system with a high penetration of renewable energy - SYSLAB
SEP Syddanmark
Smart building indeklimaregulering
Smart City Kalundborg
Smart Copenhagen – Power balancing and storage I
Smart Energy Island
Smart Energy networks Partnership – Research, development, demonstration
Smart grid fjernvarmesystemer for lavtemperatur
Smart Grid i forklædning
Smart Grid i Landbrug på Samsø
Smart Grid Open
Smart grid-styring til Kolding central renseanlæg
SmartGen, efficient identification of opportunities for distributed generation based on Smart Grid technology
Solid oxide electrolysis for grid balancing

SOSPO - Secure Operation of Sustainable Power Systems
Sovarme kombineret med varmepumper
Special programme geothermal/large heat pumps - IEA HEAT Pump Programme Annex 47...
STEPS Erhverv
STEPS, Strategisk tværkommunal energiplanlægning Sjælland
Store varmepumper til fjernvarme (svaf)
Strategic research alliance for Energy Innovation Systems and their dynamics - Denmark in global competition (EIS)
Styring, beskyttelse og fleksibelt el-forbrug i LV-net
SUSTRANS - Enabling and governing transitions to a low carbon society
SYMBIO
SYNFUEL
Synliggørelse af elforbrug via online trådløs kommunikation med en bygnings elmåler
System services from small-scale distributed energy resources
Systems with high level integration of renewable generation units
Task 3 of DESIRE project
Test-en-elbil (CLEVER)
Thermcyc
TinyPower
TotalFlex
Towards solid oxide electrolysis plants in 2020
Udvikling af damvarmelagre
Udvikling af lågkonstuktioner for store damvarmelagre
Udvikling og demonstration af lavenergifjernvarme til lavenergibyggeri
Ultra-høj-temperatur hybrid varmepumpe
Ultra-lavtemperaturfjernvarme i nye områder
Ultra-lavtemperaturfjernvarme i boligblokke
Varmeplan Danmark
Varmeplan Danmark 2010
Varmepumpe kombineret med kondenserede kedel
Varmepumpe til brugsvand i forbindelse med lavtemperaturfjernvarme
Varmepumper i eksisterende bebyggelse - Fase 1b systemdesign, komponenter og verificering
Varmepumper med lodrette boringer som varmeoptager
Virtual Power Plant for Smart Grid Ready Buildings
Værktøj til økonomisk og miljømæssig analyse af hybridanlæg til fjernkøling og fjernvarme - fjernkøl 2.0
Wind power and large-scale heat pumps for district heating in Århus
ZEB - Strategic research centre on zero emission buildings

Appendix C – Selected Nordic projects

This appendix provides a list of the Nordic projects selected for the study.

Selected Nordic projects with a smart energy focus.

Project name
Managing Smart in Smart Grid (MSiSG, NO) – reducing electricity consumption in households and building through grid and price management
IHSMAG (NO, DK and SP) – overview of RDD activities and country specific conditions for Smart Grid, effects of Smart Grid solutions based on everyday practices, regulation and the electricity system, and develop design criteria for Smart Grid solutions
IMPROSUME (NO, DK and SE) – study of and new business models and new roles for households and SMCs as Smart Grid consumers and producers (drawing on experiences with ESCO, ESP, VPP etc.) questioning simple price and contract models
Market based Demand Response (NO) – with the purpose of changing peak loads the project focus on remote control of water heaters by smart meters and varying prices based on spot markets
Demo Steinkjer (NO) - local test of smart meters and dynamic prizing with 4500 users
Smart Energy Hvaler (NO) - living lab with holiday homes, solar panel and small wind turbines using smart meters as consumption information eventually also including dynamic pricing with 6700 users
Electricity Demand Knowledge (EIDeK, NO) - electricity consumers response to hourly prices
Miljøgevinst ved velfungerende AMS i full skala (M-AMS, NO)
Demo Lyse (NO) – smart metering demonstration project 5000 users
Matning 2009 (SE) – installation of smart meters in Gothenburg including data collection of consumption
Pilot stydy Vallentuna (SE) – automation of heating based on heat pumps and sensors based on weather forecasts to move power loads
Charging infrastructure (SE) – support for charging station for electric vehicles
Customer value proposition smart (SE)
Elforsk Smart Grid program (SE) – installation of smart meters
Storstad smart metering (SE) – installation of smart meters
Stockholm Royal Seaport, Urban Smart Grid (SE) – integration of solar, wind, electric cars, ship batteries, smart appliances, smart meters, heating grid and demand management into a Smart Grid in a local area to be a demonstration of a sustainable city
Hyllie in Malmø (SE) – integration of distributed heat, cooling and power generation into a Smart Grid with customer control of consumption, including solar and large scale heat pumps, reduced transportation and visions of CO2 and distributed energy storage
Smart Grid Gotland (SE) – increasing the wind energy capacity by shifting peak loads based on price information, distributed power production for e.g. heat and storage solutions, and the management of consumer appliances still having the mainland grid as backup capacity
Beaware (FI, IT and SE) – create new service that engage households to reduce power consumption by developing software platform and sensing mechanisms monitoring and sharing data to support user action
Smart grids and energy markets (FI) – smart metering and test of dynamic pricing
Smart metering (FI) – smart metering installation
Kalastama (FI – smart metering experiments in new residential area in Helsinki
NORSTRAT (NO) – development of a Nordic power road map 2050 for carbon neutrality
CO2 electrofuel (DK) – fuel cells and tranport fuels based on electrolysis and adding hydrogen to the production of biofuels
Northsol (NO) – solar park developments in the north
Aquafeed (FI) – conversion of solar energy to hydrogen transport fuels using photo-biological organisms
ENERWOOD (KU) – exploitation of biomass based energy from Nordic forests in a policy perspective

TOP-NEST – broad focus on technology transitions
HEISEC (FI) – integrated solar energy converters
N-I-S-F-D (SE) – research on solar energy used to produce chemical fuels from CO_2 and water
STRONgrid (NO, DK, SE, FI and IS) – focus on the integration of national grids with transnational power lines demanding cross national management and marked regulations with emphasis on the planning, operation and control of the extended power grids and viewing traditional power utilities as back up capacities.
OffWind – project on further improvement of off shore wind farm efficiency through a forecasting tool for power production
GoBiGas – biogas production from forestry byproducts
Pyrogrot – oil refinery from forestry byproducts
Seabased – demonstration of wave energy technologies
Windpark Blaiken – wind turbine park in cold climate
Volvo C30 Electric – electric car for city transportation
Grøn Bil (supported by Transnova, NO) – focus on the efficiency of electric cars in relation to incentives, environmental impacts, charging infrastructure, range and driving practices
Balance management (NO, NL and BE) – integration and creation of management across the North Sea
NyNor (NO) – that focus on the production and use of hydrogen in the transport sector
GoBiGas – biogas production from forestry byproducts
Pyrogrot – oil refinery from forestry byproducts
Seabased – demonstration of wave energy technologies
Windpark Blaiken – wind turbine park in cold climate
Volvo C30 Electric – electric car for city transportation
FinSolar
Kalasatama former port area – experiments with local production of renewable energy including infrastructure for electric vehicles, energy storage, energy-efficient building automation and demand response management
LVDC pilot Suomenniemi – field test of a regional grid infrastructure
Microgrid Hailuoto – integration of energy production and consumption at island conditions
Vaasa Smart Grid pilot – improve reliability of electricity delivery and conditions for solar and wind integration in the region's households in scarcely settled villages
eStorage2 – testing and innovation of batteries and their use in electric vehicles

Appendix D – Selected European projects

This appendix provides a list of the selected European projects with a smart energy system focus. Projects have been divided in four categories: smart electricity grids, distribution, transmission, smart district heating and cooling grids, storage, other alternative fuels, and fuel cells and hydrogen.

Projects are listed in alphabetical order within each category.

European projects selected for the study.

Smart electricity grid:

Acronym	Title
BALTICGRID-II	Baltic grid second phase
CRISP	Crisp, distributed intelligence in critical infrastructure for sustainable power
ECOGRID EU	Large scale Smart Grids demonstration of real time market-based integration of DER and DR
E-PRICE	Price-based Control of Electrical Power Systems
EU-DEEP	Price-based Control of Electrical Power Systems
G4V	Grid for Vehicles - Analysis of the impact and possibilities of a mass introduction of electric and plug-in hybrid vehicles on the electricity networks in Europe
GRID4EU	Large-Scale Demonstration of Advanced Smart GRID Solutions with wide Replication and Scalability Potential for EUROPE
ICOEUR	Intelligent coordination of operation and emergency control of EU and Russian power grids
IDE4L	Ideal grid for All
INTEGRAL	Integrated ICT-platform based Distributed Control (IIDC) in electricity grids with a large share of distributed energy resources and renewable energy sources
INTEGRIS	INTelligent Electrical Grid Sensor communications
IoE (Artemis)	Artemis - Internet of Energy for Electric Mobility
IRENE-40	Infrastructure roadmap for energy networks in Europe
MEDOW	Multi-terminal DC grid for Offshore Wind
MERGE	Mobile Energy Resources in Grids of Electricity
MIRABEL	Micro-Request-Based Aggregation, Forecasting and Scheduling of Energy Demand, Supply and Distribution
MORE MICROGRIDS	Advanced Architectures and Control Concepts for More Microgrids
OFFSHOREGRID	Regulatory Framework for Offshore Grids and Power Markets in Europe: Techno-economic Assessment of Different Design Options
OPEN METER	Open Public Extended Network metering
SEPDC	Smart Electrical Power Distribution Centre
SINGULAR	Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration
SMART CITY	SMART CITY Intelligent Connecting
SMARTCODE	Smart Control of Demand for Consumption and Supply to enable balanced, energy-positive buildings and neighbourhoods
SMARTGRIDS-ETPS	Secretariat of the technology platform for the electricity networks of the future SmartGrids-ETPS
SMARTGRIDS-ETPS-III	Secretariat of the technology platform for the electricity networks of the future
SMARTREGIONS	Promoting best practices of innovative smart metering services to European regions

SUSTAINABLE	Smart Distribution System OperaTion for MAximizing the INtegration of RenewABLE Generation

Distribution:

Acronym	Title
ADDRESS	Active Distribution networks with full integration of Demand and distributed energy RESourceS
DISCERN	Distributed Intelligence for Cost-Effective and Reliable Distribution Network Operation
IGREENGRID	integratinG Renewables in the EuropEaN Electricity Grid
PLANGRIDEV	Distribution grid planning and operational principles for EV mass roll-out while enabling DER integration
POWERUP	Specification, Implementation, Field Trial, and Standardisation of the Vehicle-2-Grid Interface
SmartC2Net	Smart Control of Energy Distribution Grids over Heterogeneous Communication Networks
SUPREMAE	A Supervised Power Regulation for Energy Management of Aeronautical Equipments
SUSPLAN	Development of regional and Pan-European guidelines for more efficient integration of renewable energy into future infrastructures

Transmission:

Acronym	Title
ECCOFLOW	Development and field test of an efficient YBCO Coated Conductor based Fault Current Limiter for Operation in Electricity Networks
E-HIGHWAY 2050	Modular Development Plan of the Pan-European Transmission System 2050
GARPUR	Generally Accepted Reliability Principle with Uncertainty modelling and through probabilistic Risk assessment
GRID+	Supporting the Development of the European Electricity Grids Initiative (EEGI)
INSPIRE-GRID	Improved and eNhanced Stakeholders Participation In Reinforcement of Electricity Grid
ITESLA	Innovative Tools for Electrical System Security within Large Areas
MARINA PLATFORM	Marine renewable integrated application platform
OPTIMATE	An Open Platform to Test Integration in new MArkeT DEsigns of massive intermittent energy sources dispersed in several regional power markets
PEGASE	Pan European grid advanced simulation and state estimation
REALISEGRID	Research, methodologies and technologies for the effective development of pan-European key GRID infrastructures to support the achievement of a reliable, competitive and sustainable electricity supply
REAL-SMART	Using real-time measurements for monitoring and management of power transmission dynamics for the Smart Grid
SEETSOC	South-East European TSO Challenges
TWENTIES	Transmission system operation with large penetration of wind and other renewable electricity sources in networks by means of innovative tools and integrated energy solutions
UMBRELLA	Toolbox for Common Forecasting, Risk assessment, and Operational Optimisation in Grid Security Cooperations of Transmission System Operators (TSOs)

Smart District heating and cooling grids:

Acronym	Title
CELSIUS	Combined efficient large-scale integrated urban systems
ECOHEAT4CITIES	Ecoheat4Cities Labelling scheme for DH, DC and DHC systems
EcoHeat4EU	EcoHeat4EU
ECOHEATCOOL	European heating and cooling market study
ECO-LIFE	Sustainable Zero Carbon ECO-Town Developments Improving Quality of Life across EU
E-HUB	Energy-Hub for residential and commercial districts and transport
FC-DISTRICT	New µ-CHP network technologies for energy efficient and sustainable districts
PIME'S	CONCERTO communities towards optimal thermal and electrical efficiency of buildings and districts, based on MICROGRIDS
RESCUE	REnewable Smart Cooling for Urban Europe
SDHPLUS	New Business Opportunities for Solar District Heating and Cooling (SDHPLUS)
SDHTAKE-OFF	Solar District Heating in Europe
SESAC	Sustainable Energy Systems in Advanced Cities
SOLROD	Solrod Biogas Plant Investment Project
STEEP	Systems Thinking for comprehensive city Efficient Energy Planning
STRATEGO	Multi-level actions for enhanced heating and cooling plants
SUMMERHEAT	Meet cooling needs in SUMMER by applying HEAT from cogeneration
SUNSTORE 4	Innovative,multi-applicable-cost efficient hybrid solar (55%) and biomass energy (45%) large scale (district) heating system with long term heat storage and organic Rankine cycle electricity production
UP-RES	UP-RES Urban Planners with Renewable Energy Skills

Storage:

Acronym	Title
BIOSTIRLING-4SKA	High-capacity hydrogen-based green-energy storage solutions for grid balancing
COMTES	New generation, High Energy and power density SuperCAPacitor based energy storage system
E-STARS	Zinc-Air flow batteries for electrical power distribution networks.
ESTORAGE	Solar Thermochemical Compact Storage System
Facilitating energy storage (STORE)	Solution for cost-effective integration of renewable intermittent generation by demonstrating the feasibility of flexible large-scale energy storage with innovative market and grid control approach.
HESCAP	STAtionary BAtteries LI-ion safe Deployment
HESTOR	Development of Thermal Storage Application for HVAC solutions based on Phase Change Materials
HI-C	Composite Structural Power Storage for Hybrid Vehicles
INGRID	Efficient smart systems with enhanced energy storage
JRC 2013	Facilitating energy storage to allow high penetration of intermittent renewable energy (STORE)
NEST	Assessment of the European potential for pumped hydropower energy storage
POWAIR	A cost effective and efficient approach for a new generation of solar dish-Stirling plants based on storage and hybridization

SOTHERCO	Combined development of compact thermal energy storage technologies
STABALID	Nanowires for Energy STorage
STALLION	Safety Testing Approaches for Large Lithium-Ion battery systems
STORAGE	Novel in situ and in operando techniques for characterization of interfaces in electrochemical storage systems

Other alternative fuels:

Acronym	**Title**
ALFA-BIRD	Alternative fuels and biofuels for aircraft development
ALIVE	Advanced High Volume Affordable Lightweighting for Future Electric Vehicles
AMELIE	Advanced Fluorinated Materials for High Safety, Energy and Calendar Life Lithium Ion Batteries
APPLES	Advanced, High Performance, Polymer Lithium Batteries for Electrochemical Storage
AUTOMICS	Pragmatic solution for parasitic-immune design of electronics ICs for automotive
AUTOSUPERCAP	DEVELOPMENT OF HIGH ENERGY/HIGH POWER DENSITY SUPERCAPACITORS FOR AUTOMOTIVE APPLICATIONS
AVTR	Optimal Electrical Powertrain via Adaptable Voltage and Transmission Ratio
BATTERIES2020	BATTERIES2020: TOWARDS REALISTIC EUROPEAN COMPETITIVE AUTOMOTIVE BATTERIES
CHATT	Cryogenic Hypersonic Advanced Tank Technologies
CORE-JETFUEL	Coordinating research and innovation of jet and other sustainable aviation fuel
COSIVU	Compact, Smart and Reliable Drive Unit for Fully Electric Vehicles
COTEVOS	Concepts, Capacities and Methods for Testing EV systems and their interOperability within the Smartgrids
DELIVER	Design of Electric LIght Vans for Environment-impact Reduction
EASYBAT	Models and generic interfaces for easy and safe Battery insertion and removal in electric vehicles
eCo-FEV	efficient Cooperative infrastructure for Fully Electric Vehicles
ECOSHELL	Development of new light high-performance environmentally benign composites made of bio-materials and bio-resins for electric car application
eDAS	Holistic Energy Management for third and fourth generation of EVs:\neDAS = efficiency powered by smart Design meaningful Architecture connected Systems
eFuture	Safe and Efficient Electrical Vehicle
ELECTROGRAPH	Graphene-based Electrodes for Application in Supercapacitors
ELIBAMA	European Li-Ion Battery Advanced Manufacturing for Electric Vehicles
E-LIGHT	Advanced Structural Light-Weight Architectures for Electric Vehicles
EMERALD	Energy ManagEment and RechArging for efficient eLectric car Driving
EM-SAFETY	EM safety and Hazards Mitigation by proper EV design
ESTRELIA	Energy Storage with lowered cost and improved Safety and Reliability for electrical vehicles
EUNICE	Eco-design and Validation of In-Wheel Concept for Electric Vehicles
EUROLIION	High energy density Li-ion cells for traction
EUROLIS	Advanced European lithium sulphur cells for automotive applications
EVADER	eVADER: Electric Vehicle Alert for Detection and Emergency Response
E-VECTOORC	Electric-VEhicle Control of individual wheel Torque for On- and Off-Road Conditions (E-VECTOORC)

FABRIC	FeAsiBility analysis and development of on-Road chargIng solutions for future electric vehiCles
FASTINCHARGE	Innovative fast inductive charging solution for electric vehicles
HELIOS	High Energy Lithium-Ion Storage Solutions
HEMIS	Electrical powertrain HEalth Monitoring for Increased Safety of FEVs
HI-WI	Materials and drives for High & Wide efficiency electric powertrains
iCOMPOSE	Integrated Control of Multiple-Motor and Multiple-Storage Fully Electric Vehicles
ID4EV	Intelligent Dynamics for fully electric vehicles
INCOBAT	INnovative COst efficient management system for next generation high voltage BATteries
INGAS	Integrated gas powertrain - low emission, CO2 optimised and efficient CNG engines for passenger cars (PC) and light duty vehicles (LDV)
LABOHR	Lithium-Air Batteries with split Oxygen Harvesting and Redox processes
LISSEN	Lithium Sulfur Superbattery Exploitating Nanotechnology
MAG-DRIVE	New permanent magnets for electric-vehicle drive applications
MARS-EV	Materials for Ageing Resistant Li-ion High Energy Storage for the Electric Vehicle
NECOBAUT	New Concept of Metal-Air Battery for Automotive Application based on Advanced Nanomaterials
NEXT-GTL	Innovative Catalytic Technologies & Materials for Next Gas to Liquid Processes
OCMOL	Oxidative Coupling of Methane followed by Oligomerization to Liquids
ODIN	Optimized electric Drivetrain by INtegration
OPERA4FEV	OPerating RAck For Full-Electric Vehicle
OPTIBODY	Optimized Structural components and add-ons to improve passive safety in new Electric Light Trucks and Vans (ELTVs)
OSTLER	Optimised storage integration for the electric car
PICAV	Personal intelligent city accessible vehicle system
POLLUX	Process Oriented Electrical Control Units for Electrical Vehicles Developed on a Multi-system Real-time Embedded Platform
SafeAdapt	Safe Adaptive Software for Fully Electric Vehicles
Smart EV-VC	Smart Electric Vehicle Value Chains
SMARTBATT	Smart and Safe Integration of Batteries in Electric Vehicles
Smart-LIC	Smart and Compact Battery Management System Module \nfor Integration into Lithium-Ion Cell for Fully Electric Vehicles
SMARTV2G	Smart Vehicle to Grid Interface
SOLAR-JET	Solar chemical reactor demonstration and Optimization for Long-term Availability of Renewable JET fuel
SOLAROGENIX	Visible-Light Active Metal Oxide Nano-catalysts for Sustainable Solar Hydrogen Production
SOMABAT	Development of novel SOlid MAterials for high power Li polymer BATteries (SOMABAT). Recyclability of components.
STABLE	STable high-capacity lithium-Air Batteries with Long cycle life for Electric cars
SuperLIB	Smart Battery Control System based on a Charge-equalization Circuit for an advanced Dual-Cell Battery for Electric Vehicles
SYRNEMO	Synchronous Reluctance Next Generation Efficient Motors for Electric Vehicles
UNPLUGGED	Wireless charging for Electric Vehicles
V-FEATHER	InnoVative Flexible Electric Transport

Fuel cells and hydrogen:

Acronym	Title
ADEL	Advanced Electrolyser for Hydrogen Production with Renewable Energy Sources
AQUACELL	An innovative technology platform for the enhanced treatment of industrial wastewaters achieving cost reductions, electricity generation and enabling water reuse for non-potable applications.
ASSENT	Anode Sub-System Development & Optimisation for SOFC systems
AUTO-STACK	Automotive Fuel Cell Stack Cluster Initiative for Europe
CACHET II	Carbon dioxide capture and hydrogen production with membranes
CHIC	Clean Hydrogen in European Cities
D-CODE	DC/DC COnverter-based Diagnostics for PEM systems
DECODE	Understanding of degradation mechanisms to improve components and design of PEFC
EFFIPRO	Efficient and robust fuel cell with novel ceramic proton conducting electrolyte
FCHINSTRUCT	Preparatory activities of the joint technology initiative for fuel cell and hydrogen
GREENAIR	Generation of Hydrogen by Kerosene Reforming via efficient and low emission new alternative, innovative, refined technologies for aircraft application
H2MOVES SCANDINAVIA	H2moves.eu Scandinavia
H2OSPLIT	Water splitting catalysts for artificial photosynthesis
H2SUSBUILD	Development of a clean and energy self-sustained building in the vision of integrating H2 economy with renewable energy sources
HYCYCLES	Materials and components for Hydrogen production by sulphur based thermochemical cycles
HYDROSOL-3D	Scale Up of Thermochemical HYDROgen Production in a SOLar Monolithic Reactor: a 3rd Generation Design Study
IDEAL-CELL	Innovative dual membrane fuel cell
IDEALHY	Integrated Design for Efficient Advanced Liquefaction of Hydrogen
IRAFC	Development of an Internal Reforming Alcohol High Temperature PEM Fuel Cell Stack
ISH2SUP	In situ H2 supply technology for micro fuel cells powering mobile electronics appliances
KEEPEMALIVE	Knowledge to Enhance the Endurance of PEM fuel cells by Accelerated LIfetime Verification Experiments
LOLIPEM	Long-life PEM-FCH & CHP systems at temperatures higher than 100°C
METSOFC	Development of next generation metal based SOFC stack technology

NANOHY	Novel nanocomposites for hydrogen storage applications
NANOPEC	Nanostructured photoelectrodes for energy conversion
NEXPEL	Next-Generation PEM Electrolyser for Sustainable Hydrogen Production
NEXTHYLIGHTS	Supporting action to prepare large-scale hydrogen vehicle demonstration in Europe
PHOCS	Photogenerated Hydrogen by Organic Catalytic Systems
PREPAR-H2	Preparing socio and economic evaluations of future H2 lighthouse projects
QUASIDRY	Quasi-anhydrous and dry membranes for next generation fuel cells
RELHY	Innovative solid oxide electrolyser stacks for efficient and reliable hydrogen production
ROBANODE	Understanding and minimizing anode degradation in hydrogen and natural gas fuelled SOFCs
SMALLINONE	Smart membrane for hydrogen energy conversion: All fuel cell functionalities in one material
SOFT-PAC	Solid Oxide Fuel Cell micro-CHP Field Trials
SOLHYDROMICS	Nanodesigned electrochemical converter of solar energy into hydrogen hosting natural enzymes or their mimics
WELTEMP	Water electrolysis at elevated temperatures
ZEOCELL	Nanostructured Electrolyte Membranes Based on Polymer-Ionic Liquids-Zeolite Composites for High Temperature PEM Fuel Cell