# *Characteristics of networks in energy efficiency research, development and demonstration – a comparison of actors, technological domains and network structure in seven research areas*

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*Abstract*

*The need for more energy efficient products and technologies has increased recently in connection with meeting today's energy and environmental issues. Research, development and demonstration (RD&D) is one way of supporting technological innovation and knowledge diffusion - but there is no such thing as "just" RD&D in energy efficiency as it encompasses a multitude of different sub-areas, institutions, actors, markets etc.*

*Through the use of network analysis on unique RD&D project data from Denmark the study provides new insights into knowledge and inter-organisational networks in energy efficiency research and development. The results show how certain knowledge institutions that connect the scientific knowledge with specific applications seem to be especially important for progress in the field. Overall the study enriches the understanding of RD&D in energy efficiency with a new view on the knowledge and innovation dynamics in seven sub-areas that were otherwise simplified and regarded at a homogenous group.*

*Keywords: energy efficiency, RD&D, research collaboration, network analysis*

## Introduction

Increasing energy efficiency and enabling energy savings is often seen as a crucial part of the solution to the current energy and environmental challenges. Many opportunistic and ambitious estimates of the potentials of energy efficiency have been put forward in the last couple of decades. The main conclusion from all of these studies is that there are vast energy savings available and that they are cost effective (IEA 2012; IEA 2011; Larsen & Petersen 2012).

Since the 1970's oil crisis Denmark has been passing and enforcing ambitious energy policy combining informative, normative and economic policies together with strategic funding into research & development along with demonstration projects (Lund 2000). These historical efforts to improve energy efficiency has given a Denmark frontrunner position in terms of having an energy efficient industry and efficient households but it also has established a significant industry determined to develop and produce energy efficient technologies and products.

This paper takes a closer look on how new technological knowledge is created and applied in new energy efficient products and systems through a look at research, development and demonstration projects in Denmark. It follows the understanding of innovation and new knowledge creation from evolutionary economics and innovation systems (C. Freeman 1987; B.-Å. Lundvall 1992; Nelson 1993), which puts emphasis on the systemic nature of innovation and how it occurs in interactions of several organisations and institutions and not only inside companies. These perspectives are especially suitable with the nature of the empirical data in mind which are formed of research cooperation is connecting research institutions and commercial organisations.

The paper uses a research methodology from social network analysis (Scott 2000; Wasserman & Faust 1994) on RD&D project data from Denmark with a total of 212 projects divided into seven focus areas – *Lighting*, *Buildings*, *Behaviour*, *Industrial processes*, *Power electronics*, *Cooling* and *Ventilation*. The empirical data shows how different organisations have been collaborating on RD&D projects in the time period 2002 – 2011, which is used relational networks used in the network analysis. These networks of relations between organisations show important structures of collaborations between actors such as knowledge-institutions, producers and users.
The paper investigates and conceptualises the characteristics of energy efficiency RD&D based on those actors involved in the project and how they are interrelated. The aim will be to explain important systemic and structural dynamics while analysing the roles of the actors as a comparison of the different networks within the seven focus areas.

### *Research questions*

The study will partly act as a mapping of research efforts in energy efficiency in the Danish context illustrating the diffuse character of energy efficiency efforts in terms of different technologies, actors and relations, and partly it will be a contribution to the understanding of knowledge creation and diffuse networks in energy efficiency. The investigation will follow these research questions.
*What are the structural characteristics of the seven focus areas in energy efficiency RD&D in terms of actor composition and relations?*
*What are the major differences in network structure across the focus areas?*
*Which actor types, groups and relations seem most important for the creation and diffusion of new knowledge in the different focus areas?*

## Review of literature

### *Research in energy efficiency*

Energy efficiency research, development and demonstration is usually tied up into general energy research. Energy as a research field is therefore very incoherent and dispersed (Tijssen 1991), consisting of different large research areas such as energy production, renewable energy, energy transmission, energy efficiency etc.

There have been some studies into research and demonstration in the energy area, typically as a part of a research strategy analysis but these tend to either neglect energy efficiency or simply its role in the energy system (Kaloudis & Pedersen 2008). Actual investigations as to how RD&D in energy efficiency functions and who is involved in it does not seem to exist. One study by Lutzenhiser and Shove does however illustrate a comparison of the historical efforts in energy efficiency in the US and the UK (Lutzenhiser & Shove 1999). This study underlines the interdisciplinarity necessary in energy efficiency research and development but it mainly signifies those researchers inside research institutions and universities and does not account for the diverse patterns of cooperation across organisations in general.

There have however been many studies of energy efficiency in subareas such as in sustainable buildings (Shove 1999; Gann et al. 2010), lighting (E. Mills 1995), industry (Thollander & Palm 2013) etc. What seems to bind these subareas together are the general dynamics inherent in energy efficient solutions – the barriers to its adoption.

### *Dynamics of energy efficiency*

The largest topic in energy efficiency seems to be diffusion and adoption - more specifically the barriers towards it (Jaffe et al. 1993). Much research has been looking into the adoption of energy efficient products – whether identifying barriers at consumer- or business-level (B. Mills & Schleich 2012; Trianni & Cagno 2012) or focusing on the characteristics of the barriers (Sanstad & Howarth 1994). For a thorough overview and assessment of the barriers please see (Sorrell 2004; Palm & Thollander 2010).

These barriers illustrate some of the important innovation dynamics for energy efficient products. This is however a very rough generalisation of all energy efficient products as they are very different and their adoption is more complex because they are also dependent on product, market and sectorial dynamics. An example can be of an energy efficient circulation pump that can be seen as a general energy efficient product but first and forehand it must comply with the pump market demands such as quality, reliability and performance.

These large differences across each area cover sectorial dynamics and institutional factors, which are crucial to the understanding of each areas distinct innovation dynamics. The building sector is for instance highly regulated whereas industrial processes are less indirectly influenced (Gann & Salter 2000; Reichstein et al. 2005). These differences across energy efficiency in terms of sectors, institutions, users etc. are influential in the structure of RD&D networks, but it has not been investigated in any previous research.

### *Innovation systems and networks*

The innovation system perspective has been applied to energy technology numerous times and given way for valuable studies of the energy sector and how it interplays with energy research (Foxon et al. 2005; Gallagher et al. 2012). There is however limited research that looks into energy efficiency and energy demand using an evolutionary innovation perspective.

The innovation system theory originates from evolutionary economic thinking and the works of Joseph Schumpeter (Schumpeter 1942). Innovation systems conceptualise innovation as occurring at the intersection

between companies, universities and institutions with the creation of new knowledge as the main agent for innovation and economic growth (Nelson & Winter 1982; B.-Å. Lundvall 1992).
The innovation system perspective puts emphasis on the knowledge development as a process occurring between several actors (B.-Å. Lundvall 1992) and some studies in particular show how the knowledge and learning dynamics associated with RD&D support specific kinds of innovation (Jensen et al. 2007).

Specifically the fields of transition studies (Geels 2002) and technological innovation systems (Bergek et al. 2008) are recently giving more attention to actors and their relations. Some recent research in this field puts emphasis on the networks and network resources in technological innovation systems (Musiolik et al. 2012) as these resources are crucial in the process of formation and coordination every innovation system must undergo.

Networks play a crucial role in innovation systems studies although studies rarely focus specifically on networks (Coulon 2005). Numerous other studies have looked at organisational networks and innovation and found a positive relation between an organisations position in a network and its innovative output (Burt 1980; Tsai 2001).
Using the network analysis methodology has also been applied as a way of evaluating research programs as for instance with EU FP programs (Breschi & Cusmano 2004; Roediger-Schluga & M. J. Barber 2006; M. Barber et al. 2006). These studies specifically look at the overall structures of European research programs to identify dynamics of the networks, which is a shared approach to what is applied in this paper.

## Research methodology and data

The paper uses social network analysis in a partly explorative and partly descriptive manor on the RD&D project data from ELFORSK (DanskEnergi n.d.). Inspiration for the research methodology is drawn from network studies in other relevant research fields (e.g. Crawford 2012).

### *Research methodology*

The paper uses methods from social network analysis (Scott 2000; Wasserman & Faust 1994) to analyse the relations between actors in energy RD&D. The analysis will consist of two levels – an overall network-level analysis and a more actor focused structural-level.

The analysis also relies on qualitative data in the interpretation of certain actors and their relations. This data is collected through a thorough desktop research along with general knowledge of the research projects and the technological domains involved.

The network analysis is carried out in the UCINET software – version 6 (Borgatti et al. 2002).

#### *Network-level*

At the network-level the analysis uses the basic network metrics of Density and Avg. Distance (Wasserman & Faust 1994; Scott 2000). The density of a network is the ratio between the number of relations and the maximum number of relations possible in the network if all actors were connected and it is very valuable in understanding overall network interrelatedness. The average distance in networks refers to the average of the distances between all combination of actors in a network and it is very useful in the understanding of the size and width of a network. The metric of avg. distance is very dependent on the size of a network, which should be taken into account when comparing these.

#### *Structural-level*

At the structural-level of the analysis the main method will be structural equivalence (Burt 1976). Two nodes or actors are said to be structurally equivalent if they have the same relationships to all other nodes. It is however rarely the case that several nodes have identical relations so when the method is operationalized a margin of error is introduced. In this paper the method is used to reduce the seven large networks and create groups of actors, which to some degree are structurally equivalent in the network. This reveals the basic structural characteristics of the seven networks and an analysis of the important relations between actors and groups of actors in the networks are possible.

## *Data collection and handling*

The data originates from the ELFORSK research fund that was founded and administrated by the Danish Energy Association. From 2002 and forward approximately 3.35 Million € has been offered per year to co-fund research, development and demonstration (RD&D) with the aim of developing new energy efficient technologies. They state their aim as: "ELFORSK supports projects with the purpose of securing a more efficient use of energy, with the outset in electricity. ELFORSK emphasises that the results are realized in actual energy savings, more efficient production processes, jobs and exports as well as an increased awareness in society about efficient use of energy".

ELFORSK provides funding for applied research projects in seven separate focus areas within energy efficiency. See table 1. Between 2002 and 2011, 212 projects have received funding with approx. 400 unique actors involved. As the emphasis is on actual energy savings the research is somewhere between applied research and specific product development. ELFORSK encourage that projects have a mix of companies, research institutions, users and universities involved, which makes the relational data quite unique.

**Table 1 - Overview of project data**

| Focus area: | Behaviour | Buildings | Cooling | Industrial processes | Lighting | Power electronics | Ventilation |
|---|---|---|---|---|---|---|---|
| # of projects | 57 | 36 | 25 | 25 | 30 | 10 | 21 |
| # of organisations | 143 | 73 | 83 | 72 | 73 | 29 | 55 |

For each of the 212 projects the following data were collected.

| Focus area: | Participants: | Organisation: | Type of participant: |
|---|---|---|---|
| Classified as one of seven focus areas.<br><br>*Behaviour, Buildings, Cooling, Industrial processes, Lighting, Power electronics* or *Ventilation* | Name of the individuals on each project.<br><br>Approx. 6,5 participants per project. | Name of the organisations involved. It is possible to have multiple participants from the same organisation.<br><br>Approx. 3,5 organisations per project | Classified as a type of participant on the project.<br><br>*University, Consultant, User*[1], *Technological Institute, Energy Company* or *Producer*. |

## *Data interpretation*

The data is interpreted as relational data in the way that individuals are related if they have participated on a project together. Furthermore, is it assumed that organisations are related to other organisations if they have had employees that have participated on joint projects. These assumptions form the basis of the network data in this paper.

So the membership on projects is regarded as a relation in the network. The strength of the relations is determined by the number of people from each organisation whom are participating on each project. As the focus is on organisational relations the data is changed from two-mode (organisation to project) to one-mode (organisation to organisation).

Historical development is of great importance in an analysis, which uses a systemic and evolutionary perspective. This would intuitively mean that the networks development over time would be the aim of the analysis but in this research the focus is on the comparison of the existing networks and not their evolution

[1] Meaning a company or institution where the outcome of the project will be implemented

over time. The data consists of projects conducted over a nine year time period and they are viewed as accumulated relations to establish knowledge networks within each focus area. This can be regarded as a static view on an evolutionary process.

FIGURE 1 shows the distribution of the organisations participating where out of the 398 organisations approx. 45% have done more than one project or had multiple persons on one project. Approx. 13% of the organisations have been involved in more then five projects or had five or more participants involved in one or more projects. This distribution of participating organisations shows an exponential development, which is appropriate for further network analysis as there is a clear difference in the number of relations between actors.

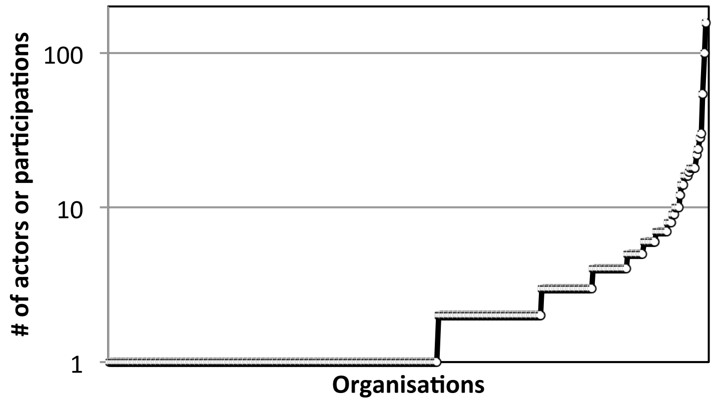


**FIGURE 1 - The distribution of organisations and participation in projects**

### *Overall characteristics of the relational data*

The structure of the empirical data naturally follows the structure of the research projects supported by ELFORSK. An understanding of the projects and the data is therefore vital for understanding the network analysis and the results.
The research projects have different sizes and compositions of participants. FIGURE 2 shows the average project composition in each of the seven areas. The major differences are the size of the projects and the type of organisation that is participating. Here an indication of how the focus areas are interrelated with the network structure begins to emerge. This will be used further in the network analysis.

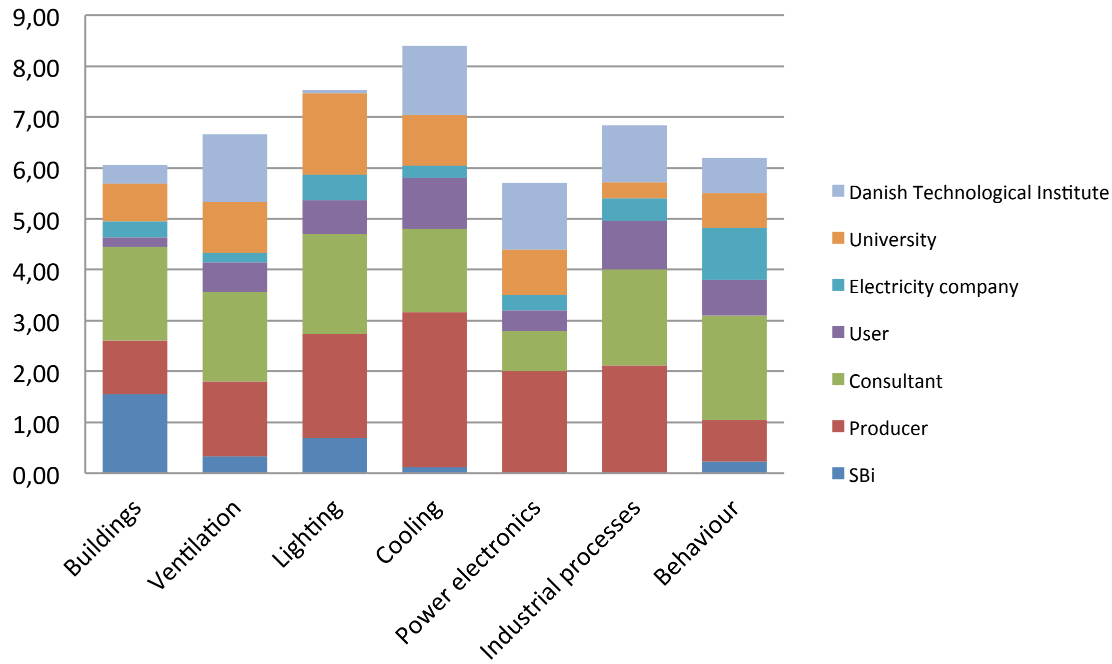


**FIGURE 2 - Actor overview and distribution - per project (ELFORSK 2002 - 2011+)**

Across the seven focus areas there are some shared organisations that participate in projects in multiple areas. Table 2 shows the percentage of shared organisations between the areas. There are more or less shared organisations depending on whether there are overlapping technological areas as for instance with *Industrial* and *Ventilation*. Furthermore is there also differences in the type of organisations there are involved in each area. Organisations such as *Universities* and *Consultants* are assumed to be involved in multiple areas, where as a small technology provider is not.

**Table 2 – Percentage of shared organisations between focus areas.**

| | Industrial | Lighting | Buildings | Cooling | Ventilation | Behaviour | Power Elec. |
|---|---|---|---|---|---|---|---|
| Industrial | 100,0 | 8,2 | 6,6 | 15,1 | 24,6 | 12,5 | 27,6 |
| Lighting | 8,3 | 100,0 | 17,1 | 8,1 | 14,0 | 13,9 | 31,0 |
| Buildings | 6,9 | 17,8 | 100,0 | 14,0 | 21,1 | 15,3 | 20,7 |
| Cooling | 18,1 | 9,6 | 15,8 | 100,0 | 17,5 | 12,5 | 13,8 |
| Ventilation | 19,4 | 11,0 | 15,8 | 11,6 | 100,0 | 9,7 | 34,5 |
| Behaviour | 25,0 | 27,4 | 28,9 | 20,9 | 24,6 | 100,0 | 37,9 |
| Power Elec. | 11,1 | 12,3 | 7,9 | 4,7 | 17,5 | 7,6 | 100,0 |
| # of projects | 72 | 73 | 76 | 86 | 57 | 144 | 29 |

*Data structure and validity*

There are certain limitations to the study based on the available data and how it is interpreted.

- There are large differences in the number of projects within each focus area, which will limit the comparison between them. This is for instance the case for *Behaviour* and *Power electronics*. This should however not change the final characteristics of the areas, as this is relatively independent of the size.
- In the original project data there is one project manager indicated on each project. The fact that one of the participants is the project manager is not included in the network analysis, as it would not change the relations, only the interpretation of actual roles in the network.
- There are clearly differences in the scope of the focus areas. Some target a specific technological area (e.g. *Lighting, Ventilation, Cooling*) whereas the areas of *Behaviour*, *Buildings* and *Industrial processes* are different with regards to their scope and delimitations. This is however also the strength of the data and it will be discussed further later in the paper.

## Results

The results of the network analysis will be derived from two levels of analysis. The first level will be the overall network level where a comparison will be made based on a two key parameters (Density and distance). The second level will be a structural level analysis to determine the structural characteristics of the different areas based on the participating organisations and their relations.
The quantitative measures gained from the network analysis methodology are interpreted in a qualitative approach to best understand the dynamics of the focus areas.

### *Network-level*

At the network level the comparison of the seven networks will be based on two parameters, i.e. network density and average distance.

#### *Network density*

The density of a network is a simple relation between its total number of relations and the number of paired nodes. A high-density network can mean a more interrelated network where for example knowledge is able to flow easier compared to a low-density network ((Burt 1976; Burt 1980)). Higher density will also limit the importance of intermediaries and knowledge brokers to facilitate flows in the network.

FIGURE 3 shows the densities of the seven focus areas with *Behaviour* having the lowest and *Power electronics* having the highest. As mentioned earlier should a comparison using the *Power electronics* area be done with caution, as the data are somewhat incomparable. It is however clear that the focus areas defined by a technological area i.e. *Lighting*, *Cooling* and *Ventilation* have a more dense network than those defined by a broad application area i.e. *Behaviour*, *Industrial processes* and *Buildings*. This can be explained by the homogeneousness of the areas with *Behaviour* being the extreme where many different organisations are working on many different ways of influencing energy using behaviour. On the other side of the scale we have the more stable areas of *Cooling* and *Ventilation*, which opposite to *Behaviour* is embedded in structures outside the network for example through industry, sector, suppliers etc.

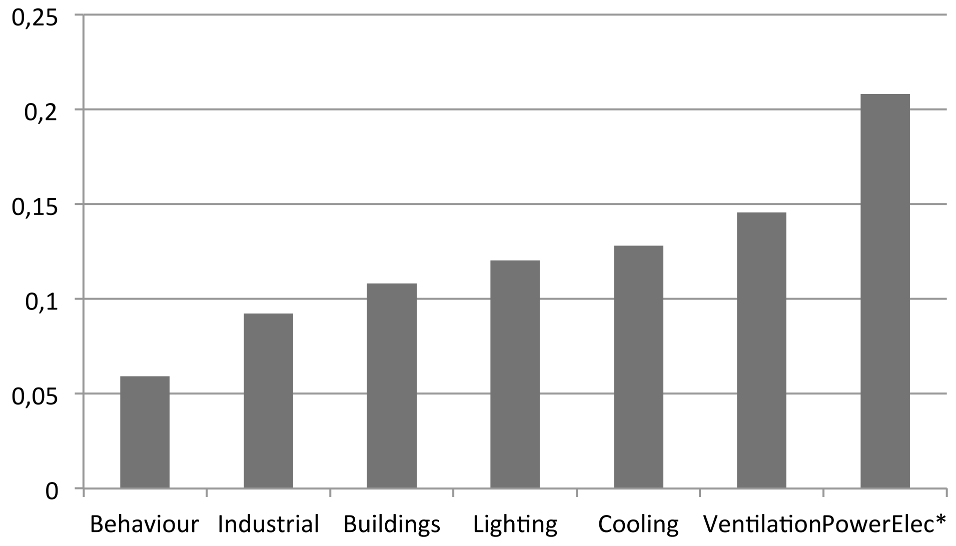


**FIGURE 3 - Network density**

*Distance*

In almost every network there are actors, which are not adjacent to each other. For these to connect they must go through other actors. Distance in networks refers to the number of relations there must be present for two actors to stay connected. The average distance (average geodesic distance) is the mean of the shortest path lengths among all connected pairs in the network. Having a network with short distances makes knowledge diffusion to the entire network quicker.

There are no large variations in the average distances in the networks – See FIGURE 5. It is however clear that the application based focus areas i.e. *Industrial* and *Behaviour* are more diverse and in general have larger distances between distant actors. This hypothetically makes it slower to fully diffuse knowledge in the application-based networks.

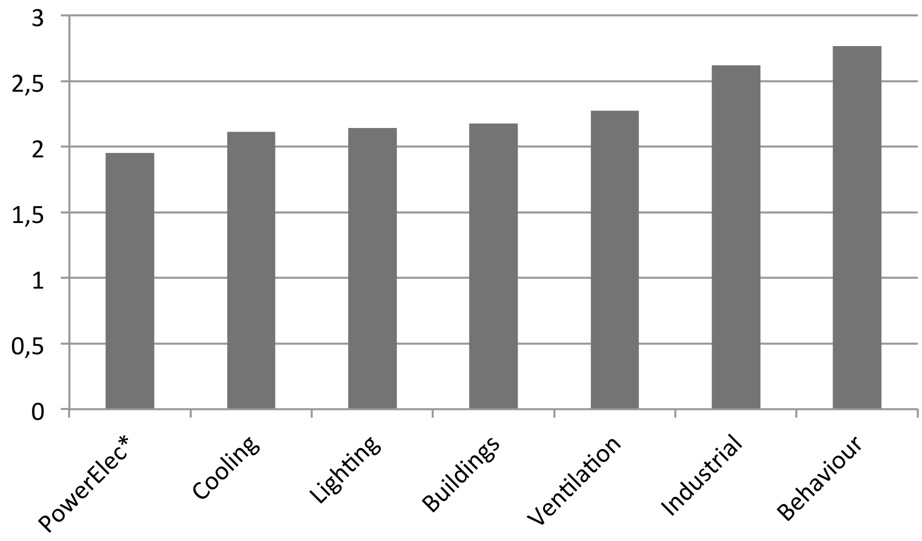


**FIGURE 5 - Average distances in the networks**

*Summary at network level*

Summarising the analysis at the network level shows slight variations across the seven focus areas. The technology-based areas of *Ventilation*, *Cooling* and *Lighting* tend to have more dense networks with shorter distances between actors, whereas the more application-based areas of *Buildings*, *Industrial processes* and *Behaviour* show less interconnected networks with more diverse actors and relations. These are in coherence with the descriptive statistics in Figure 2 and Table 2.

### *Structural-level*

The second level of analysis is at the structural level where the aim will be to identify the structural characteristics of each focus area. The structural equivalency method from social network analysis by Ronald S. Burt (Burt 1976) is used to enable a simplification of the large research networks so an understanding of the structural characteristics of each is possible. Through this methodology and the resulting graphic representation of each of the seven areas it possible to analyse how and where the important interactions in the networks are occurring.

#### *Lighting*

The research area of *Lighting* is concerned with the development and application of low energy lighting solutions primarily using LED technology to achieve energy savings. The area shares several organisations with *Buildings* and *Behaviour* (Table 2) that is logical as *Lighting* shares many elements with energy use in buildings and end-user interaction.

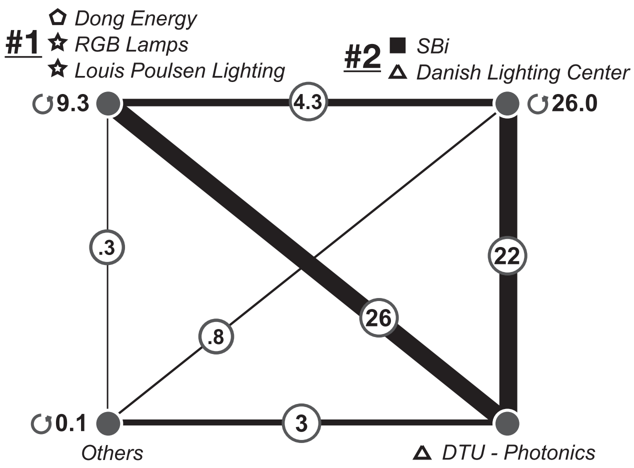


FIGURE 6 - Structure of the *Lighting* network


FIGURE 7 - Legend for network structure graphs

The network is driven by DTU Photonics as the focal actor with strong relations to two secondary groups. The first secondary group consists of business and application resources in the form of two lighting producers and an energy company. The second group - #2 – consists of research and technical consulting organisations contributing with technical and system resources. These two secondary groups have little interaction with the rest of the network, which are mainly involved through the focal actor.

*Lighting* outlines a structure where it seems that organisational and technological resources and knowledge are originating from the focal actor and where application knowledge is included through the two secondary groups by the focal actor.

*Behaviour*

The research area of *Behaviour* is a very diverse and somewhat diffuse area where energy savings are realised through efforts in technical, organisational and social aspects. This can be seen in Table 2, which illustrates how *Behaviour* is sharing many organisations with all other focus areas. This diversity in organisations and their relations result in a complex network structure.

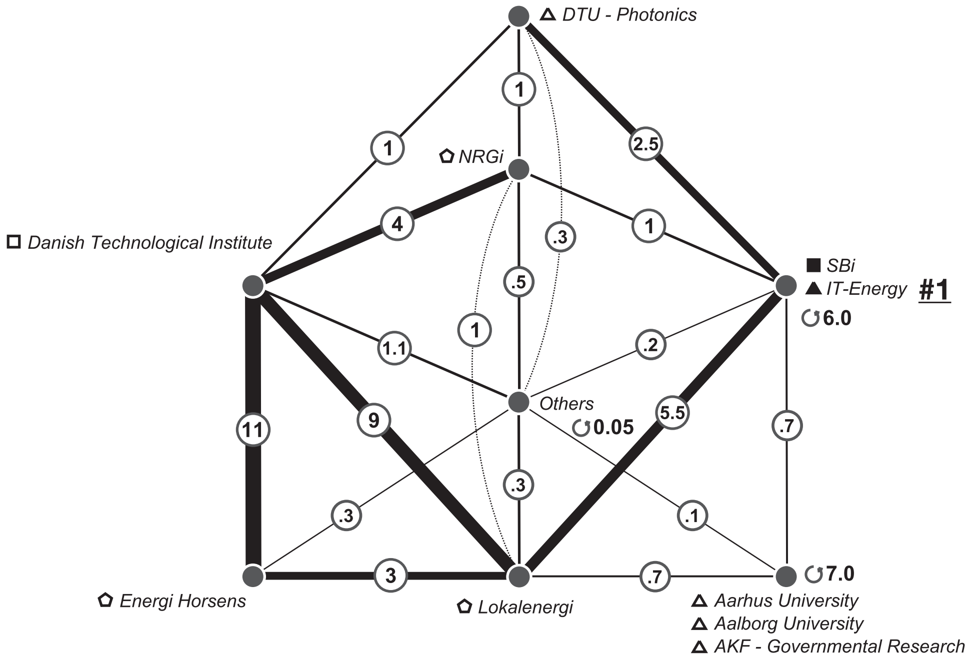


**FIGURE 8 - Structure of the *Behaviour* network**

The driver of the network is not one focal actor as seen in *Lighting* but more a constellation of multiple actors. The DTI is acting together with three different energy companies while two of the energy companies also are interlinked with a grouping (#1) of SBi and a consulting company. This is an interesting constellation where the two energy companies are combining the two competing knowledge institutions. This clearly illustrates the diverse nature of *Behaviour* where the heterogeneousness nature of the energy saving solutions leads to a complex relational structure.

*Power Electronics*

The research area of *Power electronics* is aiming to either improve the efficiency of electronic systems or introduce electronics to enable energy savings for instance through control and automation. The research area is under represented in the empirical data, which must be considered in the structural analysis.

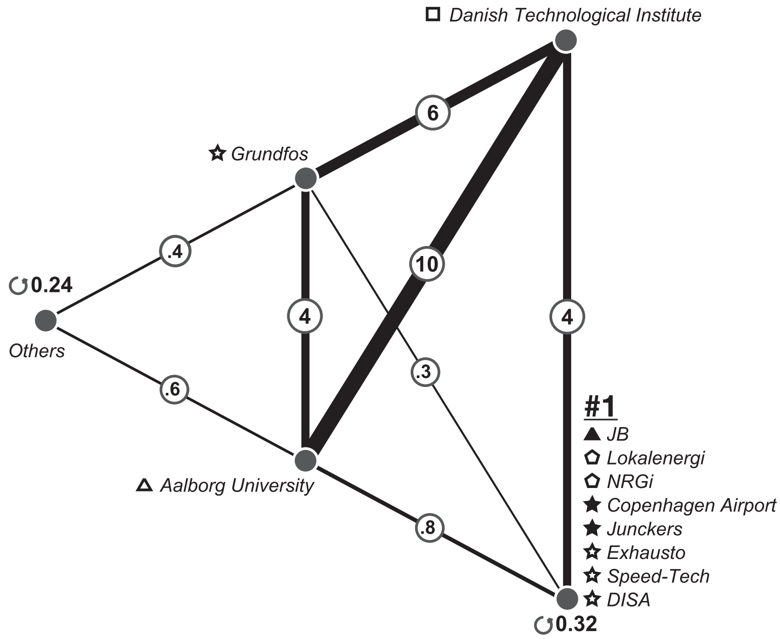


FIGURE 9 - Structure of the *Power electronics* network

The network has a constellation of actors driving the network. The DTI, a producer and a university are highly interrelated and besides the main constellation there is a large support group, which includes producers, users and energy companies. The secondary group is primarily involved through DTI.

*Industrial processes*

The research and development area of *Industrial processes* is aiming to reduce energy consumption through the optimisation of production facilities in all industrial sectors. These kinds of projects are usually context specific to each type of production facility and each specific site, making generalisation especially difficult in this area. The projects require special knowledge on a multitude of industrial processes and their interaction in a large production system.

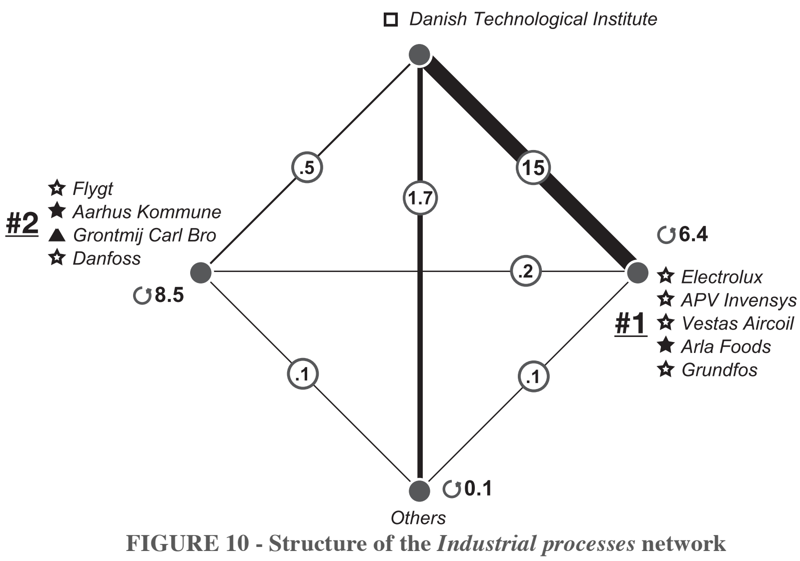


FIGURE 10 - Structure of the *Industrial processes* network

The focal actor in the network is DTI, which only has a strong relation to group #1 while having relatively weak ties to group #2 and to the rest of the network. Group #1 consists of five producers and one user and act as the preferred project partners together with the DTI. The DTI act as project organisers and are knowledgeable of the overall production systems, while they include technologies from individual producers when necessary.

Group #2 seems to have very little interaction with other groups, which can be explained, by their high internal interaction. The group consists of multiple types of actors, which could indicate that they are sufficient with each other and only include outsiders when necessary.

*Cooling*

The research area of *Cooling* is aiming at increasing energy efficiency in two contexts. Cooling and air conditioning refers to the indoor environment in houses and offices while cooling also can be related to refrigeration in food- and retail-sector. These two types of technologies are similar but its application is very different which will have influence on the network.

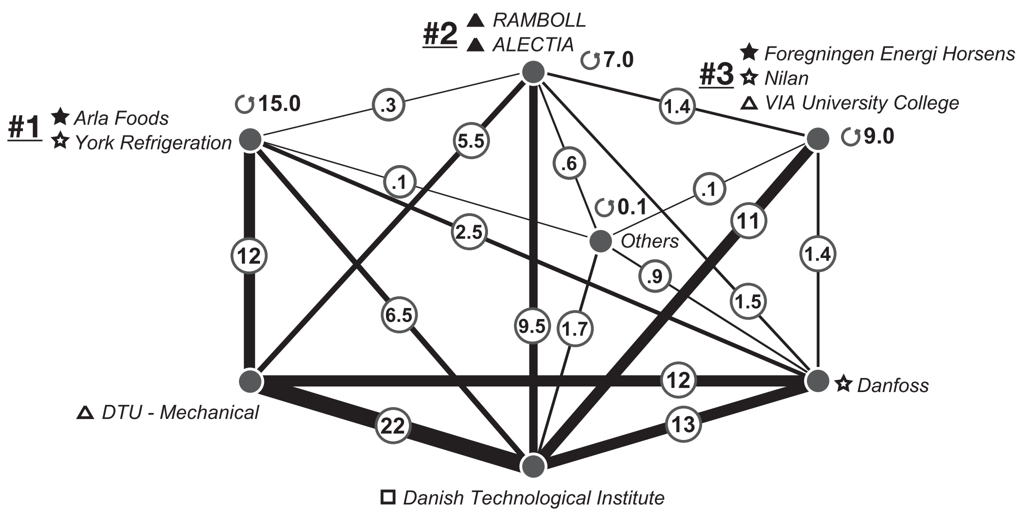


**FIGURE 11 - Structure of the *Cooling* network**

The network consists of a constellation of driving actors with three supporting groups. DTI, DTU and the producer Danfoss are making up the constellation while three main supporting groups are connected through different parts of the constellation. The constellation itself has scientific-, application- and organisational-knowledge with very strong supporters contributing with contextual knowledge on either cooling and refrigeration (#1) or cooling and ventilation (#3). Furthermore is group #2 containing two building consultants involved to provide knowledge on the building integration aspects of cooling.

The very high density of the network also indicates that the network is very interconnected and that the "power" is distributed among several actors even though there are two separate groupings attached to the constellation.

*Ventilation*

The research area of *Ventilation* is aiming to lower the use of energy in ventilation systems for homes, offices and industrial buildings, which primarily mean optimising fan, duct and heat recovery systems.

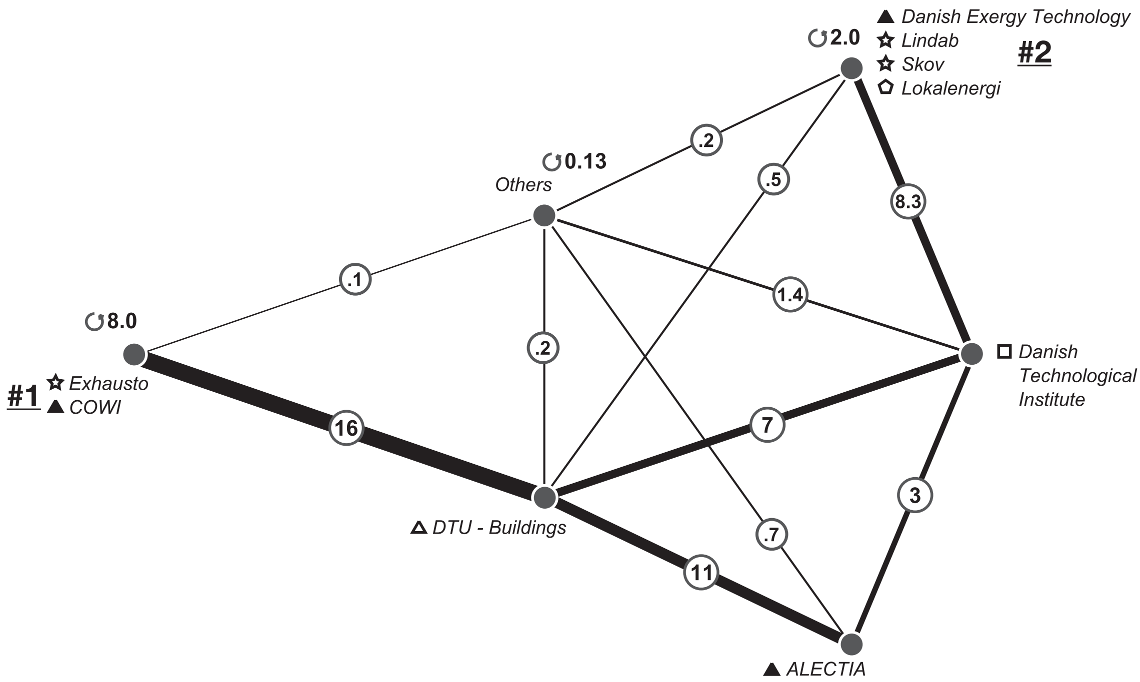


**FIGURE 12 - Structure of the *Ventilation* network**

The network shows a constellation of DTU, DTI and ALECTIA with strong support coming from two separate groupings to either DTU or DTI. The two supporting groupings appear similar in their actor composition with a combination of producers and technical consultants indicating a competitive aspect to the constellation.
The rest of the network seems involved through multiple actors, which supports the occurrence of a broad constellation.

*Buildings*

The research area of *Buildings* is aiming to improve primarily the non-energy using elements of the houses, offices and industrial buildings. This means improving the building envelope, windows, building techniques etc. for new and existing buildings.

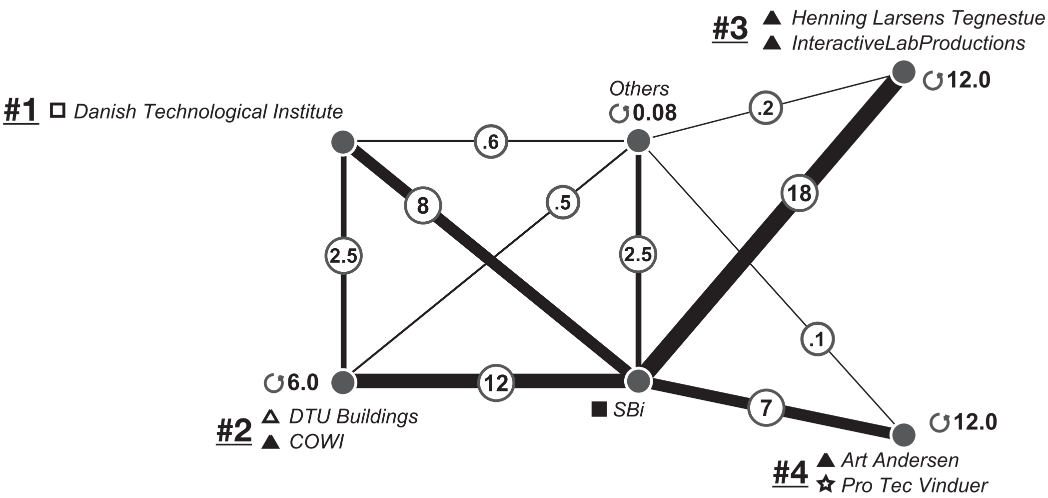


**FIGURE 13 - Structure of the *Buildings* network**

The network has SBi as the focal actor with strong support coming from several groups. The two sides of the groupings (#1 & #2 vs. #3 & #4) show two important elements in the area of energy efficiency in buildings. The research area is a merger of technical knowledge coming from research institutions and technical consultants (#1 & #2) together with architectural knowledge coming from architectural consultants (#3 & #4). The rest of the network seems to be involved primarily through the focal actor.

The construction companies themselves seem however to be missing from the network completely, which seems as an inefficiency of the network.

*Summary at the structural level*

**The networks show distinct differences in structure across the seven research areas.**

Table 3 shows a summary of the structural level analysis.

The clear differences are in whether a network has a focal actor or a constellation of actors driving the network. DTI, DTU and SBi seem to be especially actors important across different focus areas with DTI involved in almost all networks and SBi acting as the focal actor in more building-related areas (*Buildings* and *Behaviour*). There also seems to be differences in the arrangement of supporting groups to whether there are different application areas within a focus area, which for instance is the case with *Cooling*, or whether there are competing groups connected to different part of the main constellation, as is the case with *Ventilation*.