Energy 124 (2017) 492–501

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Cross-border versus cross-sector interconnectivity in renewable energy systems

Jakob Zinck Thellufsen*, Henrik Lund

Aalborg University, Department of Planning and Development, Skibbrogade 3, 9000 Aalborg, Denmark

A R T I C L E I N F O

Article history:
Received 7 November 2016
Received in revised form
13 February 2017
Accepted 19 February 2017
Available online 20 February 2017

Keywords:
Energy systems analysis
EnergyPLAN
Interconnection
Transmission
System integration
Smart energy systems

A B S T R A C T

In the transition to renewable energy systems, fluctuating renewable energy, such as wind and solar power, plays a large and important role. This creates a challenge in terms of meeting demands, as the energy production fluctuates based on weather patterns. To utilise high amounts of fluctuating renewable energy, the energy system has to be more flexible in terms of decoupling demand and production. This paper investigates two potential ways to increase flexibility. The first is the interconnection between energy systems, for instance between two countries, labelled as cross-border interconnection, and the second is cross-sector interconnection, i.e., the integration between different parts of an energy system, for instance heat and electricity. This paper seeks to compare the types of interconnectivity and discuss to which extent they are mutually beneficial. To do this, the study investigates two energy systems that represent Northern and Southern Europe. Both systems go through three developmental steps that increase the cross-sector interconnectivity. At each developmental step an increasing level of transmission capacities is examined to identify the benefits of cross-border interconnectivity. The results show that while both measures increase the system utilisation of renewable energy and the system efficiency, the cross-sector interconnection gives the best system performance.

To analyse the possible interaction between cross-sector and cross-border interconnectivity, two main aspects have to be clarified. The first part defines the approach and the second is the construction of the two archetypes.

1. Introduction

A key component in plans for future energy systems is fluctuating renewable energy sources, for instance wind power and solar power. This is for instance shown in plans and research for Denmark [1–3], Ireland [4], the United States of America [5], Portugal [6] and Germany [7].

However, because of fluctuating renewable energy's dependency on, for instance, weather patterns, a flexibility problem is created in matching demand with production [8,9]. In current energy systems, large amounts of dispatchable power plants and combined heat and power (CHP) plants regulate the production depending on demand, hence creating the necessary flexibility [10]. In future renewable energy systems, it is still necessary to match production with demand, but due to the large amount of fluctuating renewable energy and reduced dispatchable power capacity, other solutions have to be identified to reach sufficient flexibility.

Based on [11], who reviews a number of flexibility measures, some possible solutions can be grouped as:

- Transmission. Dealing with flexibility by allowing transmission between different energy systems, when one system has over production and the other has lack of production.
- Storage solutions. Using batteries, hydro power or fuel cells to store electricity.
- Integrated energy systems. This includes linking the different energy sectors with each other through power to heat, power to gas, CHP production, electric vehicles and other units that enable a more flexible production and utilisation of electricity. By integrating the energy system, a larger storage portfolio exists as it enables the storage of electricity as heat or gas.

While [11] suggests a number of other possible solutions, it is

* Corresponding author.
E-mail addresses: jakobzt@plan.aau.dk (J.Z. Thellufsen), lund@plan.aau.dk (H. Lund).

http://dx.doi.org/10.1016/j.energy.2017.02.112
0360-5442/

not common to compare these with each other. Ref. [11] points to several studies of the solutions analysed individually. This paper instead takes on a comparison between on transmission and system integration as they represent two distinct ways of improving the flexibility to increase the utilisation of fluctuating renewable energy. Transmission focuses on utilising the surrounding energy systems by importing and exporting electricity and as such, it represents an external view on increasing flexibility. Opposite, the integrated energy system seeks to improve the links between the different energy sectors in a single energy system, thus representing an internal view on increasing flexibility. It is a discussion between an external solution to excess electricity and an internal solution.

Both an increase in transmission and an increase in energy system integration can be seen as increased interconnectivity. Transmission is interconnection between energy systems and integration is interconnection within an energy system. Together these can be viewed as a two-dimensional approach to interconnection.

The benefits of transmission in terms of increased flexibility in systems with fluctuating renewable energy are investigated in Refs. [12–14]. These studies investigate a Europe with an electricity demand fully supplied by fluctuating renewable energy. To investigate the flexibility achieved through transmission, different levels of transmission between all European countries are investigated, see Fig. 1. Each European country has a mix of solar and wind power to supply the full electricity demand. A transmission cable interconnects Europe to utilise fluctuating renewable energy throughout the region. In a fully interconnected Europe with the entire electricity demand covered by fluctuating renewable energy and no restriction to transmission capacity, the total backup capacity corresponds to 15% of the annual electricity consumption, while without transmission cables, it is 24% of the annual electricity consumption [13]. The studies do, however, not investigate the integration with other parts of the energy system, Thus, they are not able to investigate the transmission solution in relation to integrated energy systems.

One way to approach integrated energy systems is through the concept of smart energy systems [2,15–19]. The smart energy system approach takes its offset in the point that it does not make sense to look at the separate parts of the energy system individually. To utilise the benefits converting electricity to heat, it is necessary to plan heating and electricity together. Smart energy systems are defined as:

> "[…] an approach in which smart electricity, thermal, and gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall system." [19].

Through this system integration, illustrated in Fig. 2, smart energy systems can increase the flexibility by utilising electricity in other sectors, for instance through heat pumps, electric vehicles and electrofuel production. Furthermore, these solutions give an array of storage opportunities in thermal storage, batteries and fuel tanks. By linking these sectors, the flexible production can come from CHP plants [19]. Examples of smart energy system plans can be found for Denmark [2,17], Ireland [20] and the European Union [10]. These examples, however, do not investigate the possible implication of transmission cables in relation to system integration.

None of these studies investigates and compares the two solutions [12–14]. only include the electricity sector, thus automatically ruling out the possible benefits of increasing the integration. The Smart Energy System [2,15–19] primarily focuses on building integrated energy systems to resemble 100% renewable energy systems, and while it does include transmission in the IDA Energy Vision [2], it is always with the focus of cross-sector interconnectivity to deal with excess electricity production from fluctuating renewable energy.

Therefore, this study investigates the relation between cross-sector and cross-border interconnectivity. The goal is to see the benefits of both individually, but more importantly, whether and to which extent the two types of interconnectivity can work together to increase flexibility in energy systems with high amounts of fluctuating renewable energy.

This is done by interconnecting two archetype energy systems. One represents a Southern European energy system and the other a Northern European energy system. The systems will be connected to each other through transmission cables to investigate cross-border interconnectivity. To investigate cross-sector interconnectivity, both systems will take a number of steps towards the Smart Energy System design. Based on the extent to which the system utilises the total fluctuating renewable energy production and reduces primary fuel use in the energy system, the study discusses the idea of interconnectivity.

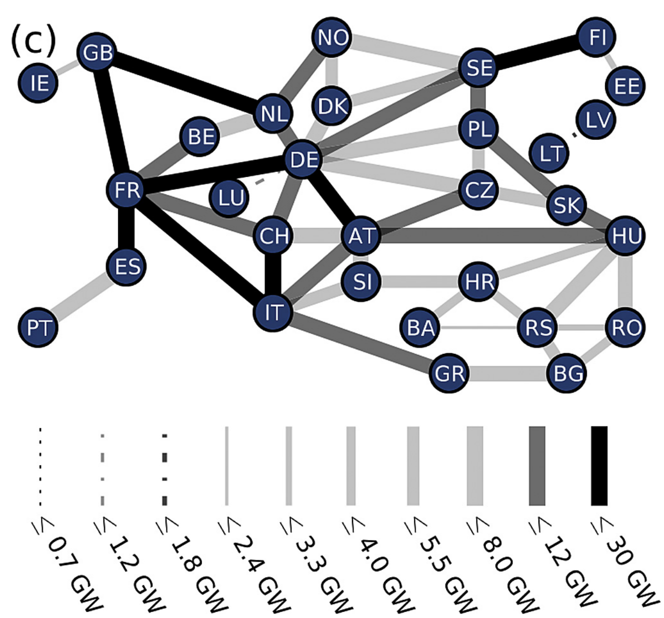

Fig. 1. Example of layout of transmission grid in a cross-border interconnected Europe [13].

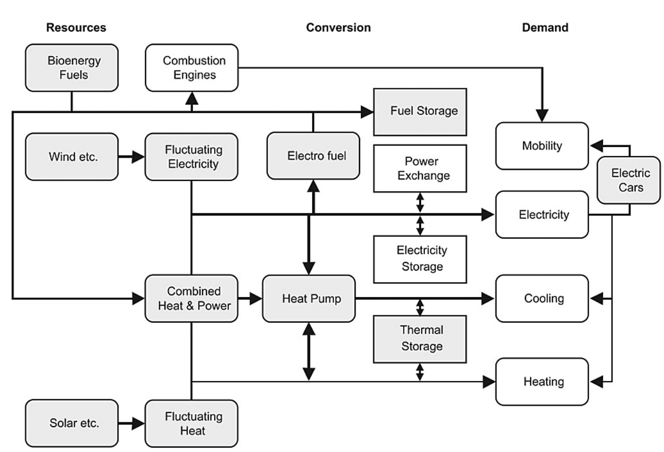

Fig. 2. Sketch of the cross-sector interconnectivity found in the smart energy approach [10].