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Publication date:
2015

Document Version
Early version, also known as pre-print

Link to publication from Aalborg University

Citation for published version (APA):
Thellufsen, J. Z. (2015). *Smart Cities and National Energy Systems*. Paper presented at 10th Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik, Croatia.

Smart Cities and National Energy Systems

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ABSTRACT

Energy system analysis follows two tracks, either through plans for future transitions of national energy systems, or local development of smart cities and regions. These two tracks seldom overlap. National plans neglect the local implementation of intermittent renewable technology and use of local resources, and smart cities and local development do not relate to national targets and fail to evaluate sub-optimization. Thus, there is a need for approaches that help researchers creating links between country analyses and local energy system transitions. This paper investigates the effects of such an approach, by investigating Western Denmark. By splitting Western Denmark into regions, it is possible to create individual energy systems for each region. Through interconnection, these regions can exchange electricity with each other. This enables analyses of interaction between smart cities and national energy systems.

KEYWORDS

Energy system analysis, local energy planning, national energy planning, energy planning, energy systems, renewable energy, smart energy systems

INTRODUCTION

Due to climate change caused by CO_2 emissions from usage of fossil fuels [1], countries and researchers are planning and investigating future renewable energy systems to facilitate a move away from fossil fuels. Examples of this exists in Denmark with both the Danish Energy Agency [2] and researchers [3] suggesting 100 % renewable energy systems, other examples are Ireland [4], USA [5], Brazil and Portugal [6]. All these plans focus on overall transitions to renewable energy. This means, that they work on a country or state level of transition. Thus these plans do not take local planning into account. Because wind turbines, solar panels and other renewable energy sources are local resources there has to be an increased focus on local energy planning. One way of looking at local energy planning and resources is Smart Cities [7]. Smart Cities as a concept does not only focus on energy, but two of the primary elements are energy demand and supply [8]. When discussing these two elements, it is important to mention that the city has to be seen in relation to the region and the country. This is acknowledged by [9] that highlights that the Smart City has to be seen in relation to the region. Overall this could be labelled as Smart Regions. But even these Smart Regions has to be linked to the countries or states they exist within. The reason is to avoid sub optimisation in cities and regions.

Due to the need for local planning, research is also focusing on regional, municipal and city plans for renewable energy systems. Examples are the case of a local energy plan for Aalborg [10] and Frederikshavn [11,12] both in Denmark, and the South West Region of Ireland [13].
These studies highlight different approaches for taking the national energy system into account, when modelling local energy systems.
In the case of Frederikshavn [11,12], the modelling seeks to minimise electricity exchange with the remainder of Denmark. The exact relation to the development of the rest of Denmark is

discussed in relation to [14], but not directly included in the calculations of the local energy system.

The study of Aalborg [10] includes national perspectives, by excluding local resources and activities that does not have primary local use, and instead allocates these resources based on share of national population. In this case Aalborg municipality receives the benefits but not the burdens of these parts of the energy system, such as industrial waste heat. This approach allows for the national development to be taken into account in modelling local systems, but the downside of such an approach is that the system modelled is not equal to the actual layout of the current energy system.

A third approach, and perhaps the most widely used, is not taking into account the national system, and looking at the local system from an island perspective. An example is [13]. These studies of course have the ability of showing a way for renewable energy in the local regions, but because of the lacking perspective to the national energy system cannot say what consequences it has for national plans.

Because of this growing focus on local energy system analysis and the need for national perspectives this paper investigates a different approach. This approach seeks to model a country as separate interconnected smart regions, to enable exact modelling of each region, and still being able to discuss the consequences for national development. The study applies the approach on the case of Western Denmark modelled as three regions. The goal is to identify what consequences it has to model a country as regions compared to modelling the country as a single entity.

METHODS

To create a tool for modelling and analysing the link between smart energy systems and smart regions, the study creates a framework within the tool EnergyPLAN. This section describes the usage of EnergyPLAN in such context and the concrete analysis of Western Denmark.

Linking Countries and Nations in EnergyPLAN

EnergyPLAN is an input/output model that simulates the energy system on an hourly basis. Inputs can be energy demands, combined heat and power plant capacities and installed capacity of wind turbines, while example of outputs are total fuel uses and CO_2 emissions. EnergyPLAN is deterministic meaning that the same inputs always generates the same outputs. Figure 1 outlines the operation of EnergyPLAN.

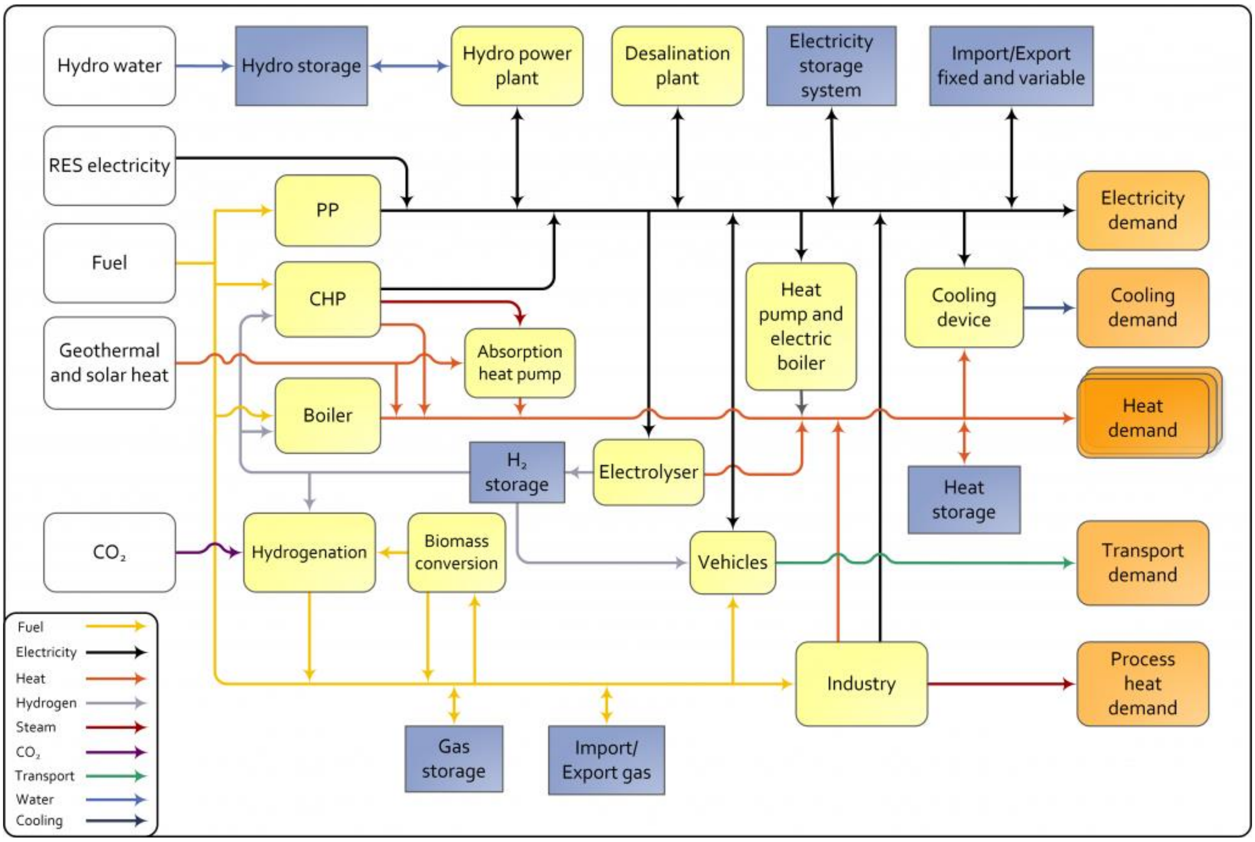

Figure 1. Operation of EnergyPLAN [15]

One of the reasons for using EnergyPLAN is that it has been applied to several cases of energy system analysis on both municipal [10], national [3] and transnational level [16]. However, there is no framework of linking these different levels of the energy system. The following describes the development of such a framework.

The goal of linking different levels of energy systems is to be able to say something about each energy system as well as the total connected system. This means that an EnergyPLAN model has to be created for each system and each system has to be analysed individually before they are connected. This has a few consequences. First and foremost, this makes it possible to say something about each individual system. Second, due to the use of technical simulation (meaning that the systems reduces fuel use, minimising the use of power plant and boiler production) and that each system is modelled individually, the systems first and foremost utilise local plants and does not take into account possible interconnection. The first run of each systems is thus an island mode operation.
From this island mode operation it is however possible to identify hours with excess production and where import is needed due to lack of capacity. The proposed method takes this offset and combines it with the assumptions from the technical optimisation in EnergyPLAN. This means that besides the import needed from lack of power plant capacity, each system seeks to import if production is happening on a power plant or if there is spare capacity in an electrical storage. From this, the goal is to both increase CHP production and better utilise renewable energy production. To identify the available importable electricity, the exportable electricity is summarized on grid level, meaning that in each hour it is possible to import from the available exported electricity. The energy systems will import only in situations where they are not exporting, and who imports first is determined based on a pre-ranking.

From this approach it is possible to identify hours of import and export between each energy system, resulting in a total demand for import/export and a distribution. This information is inserted as a fixed import/export for each system and a final run is made. Figure 2 illustrates this approach. Overall, this approach implies that each energy systems runs according to the concept of connected island mode [17].

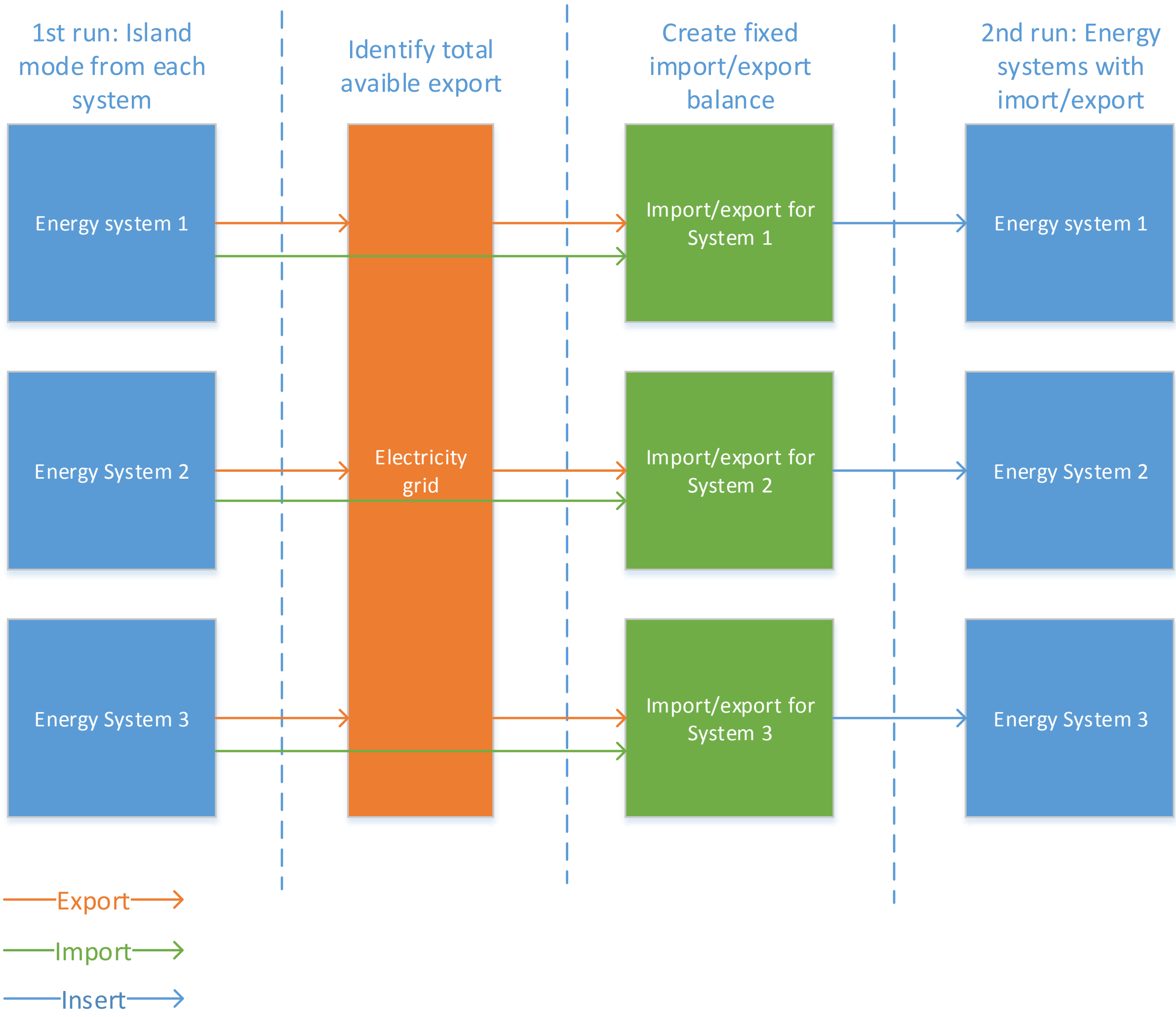

Figure 2. Model of framework for linking energy systems in EnergyPLAN

This approach is applied to the case of Western Denmark, and the development of a local smart region. The next section describes the analyses.

Model of Western Denmark

The study tests the suggested approach on the case of Western Denmark. Western Denmark is the DK1 electricity system in NORDPOOL Spot, and as such it possible to identify total electricity demand and central power plant production. In this study, Western Denmark is divided into three regions: Northern, Central and Southern. Figure 3 illustrates this division.

Figure 3. Layout of the three parts of Western Denmark

In the first analysis the three regions are modelled as a reference year of 2012, the models are based on estimates from data from Energinet.dk [18], and Danish Energy Agency [19,20]. The systems are modelled only with heat and electricity demand, and only heat and electric producing units. Thus there is no transport and no industry taken into account. Table 1 highlight main input criteria.

Table 1. Inputs for analysis 1

	Northern Region	***Central Region***	***Southern Region***	***Western Denmark***
Electricity demand [TWh]	4.17	7.32	7.11	18.6
Heating demand (Group 2) [TWh]	1.71	2.57	2.6	6.88
Heating demand (group 3) [TWh]	1.88	4.9	5.7	12.48
CHP2 electric capacity [MW]	292	400	508	1200
CHP2 heating capacity [MJ/s]	395	800	686	1967
CHP3 electric capacity [MW]	327	831	1182	2340
CHP3 heating capacity [MJ/s]	420	1131	1486	3024
HP2 heat capacity [MJ/s]	0	0	0	0
HP3 heat capacity [MJ/s]	0	300	0	300
PP1 capacity [MW]	383	855	1300	2538
PP2 capacity [MW]	0	0	0.00	0
Wind capacity [MW]	710.6	1036	852	2598.6
PV capacity [MW]	0	167	311	478
Individual HP heat capacity [MJ/s]	0	0.01	0	0.01

The goal of this analysis is to create a reference system, and to test the accuracy of the calculations. As such three types of calculations are compared:

- Western Denmark as a single entity (no regional division).
- Western Denmark modelled as regions in island mode operation without including the electricity exchange between regions.
- Western Denmark modelled as regions and including electricity exchange between regions.

These are compared in terms of two primary parameter: Fuel consumption in main electricity producing units and the net fuel use including import/export to surrounding systems. Together these two should help towards identifying to what extent the three regional systems can assist each other, and obtain better utilisation of renewable energy and combined heat and power.

The second analysis investigates that one region takes a radical different development track than the two other regions. The goal is to identify how well the tool interacts if systems follow different development tracks and thus become less equal than might be the case in the reference scenario of 2012. To model this, the Southern region shifts to resemble a CEESA 2035 [3] scenario while the Northern and Central Region remain fixed. The same comparison is made as in the first analysis. It is important to note that in both analysis 1 and analysis 2, EnergyPLAN uses technical simulation strategy 1 that balances the systems only according to heat demand. Table 2 shows inputs for analysis 2.

Table 2. Inputs for analysis 2

	Northern Region	***Central Region***	***Southern Region***	***Western Denmark***
Electricity demand [TWh]	4.17	7.32	8.11	19.6
Heating demand (Group 2) [TWh]	1.71	2.57	1.3	5.58
Heating demand (group 3) [TWh]	1.88	4.9	2.9	9.68
CHP2 electric capacity [MW]	292	400	0	692
CHP2 heating capacity [MJ/s]	395	800	0	1205
CHP3 electric capacity [MW]	327	831	700	1858
CHP3 heating capacity [MJ/s]	420	1131	616	2108
HP2 heat capacity [MJ/s]	0	0	90	90
HP3 heat capacity [MJ/s]	0	300	45	345
PP1 capacity [MW]	383	855	700	1938
PP2 capacity [MW]	0	0	200	200
Wind capacity [MW]	710.6	1036	2200	2598.6
PV capacity [MW]	0	167	311	478
Individual HP heat capacity [MJ/s]	0	0.01	14.03	14.04

RESULTS

The following sections show the results for analysis 1 and analysis 2. The results reflect on the total fuel use in the three primary electricity production units, decentralized combined heat and power (CHP2), centralized combined heat and power (CHP3) and power plant production (PP1).

Analysis 1: Reference scenario

This analysis discusses the consequences of modelling the reference scenario of Western Denmark as according to the methodology. Figure 4 shows the fuel used in CHP2, CHP3 and PP for the three different ways of modelling Western Denmark. Figure 5 shows the total fuel balance for the three models, including the net fuel consumption, identified by the changes due to yearly import and export.

Both Figure 4 and Figure 5 shows that there is not a great difference in modelling Western Denmark as one entity, as three island mode operating regions or three connected regions. There is a slight difference in power plant production and CHP from the single entity modelling and the two region based models. However, the two region based models allow for identifying consequences of local planning which is not possible with only a single large model. The reason for the very small difference between the island model and connected model is that all three systems are very similar. This means that wind turbines produce in the same time, electricity and heat demand profiles are similar, and the layout of the energy system is to a large extent the same. The consequence is that very few situations occur with import demand in one system and export demand in another system. Instead, when one system is producing excess electricity the two other regions does the same, and when there is an import demand in one region, the two others do not produce excess. The methodology does not seek to increase PP production for export.

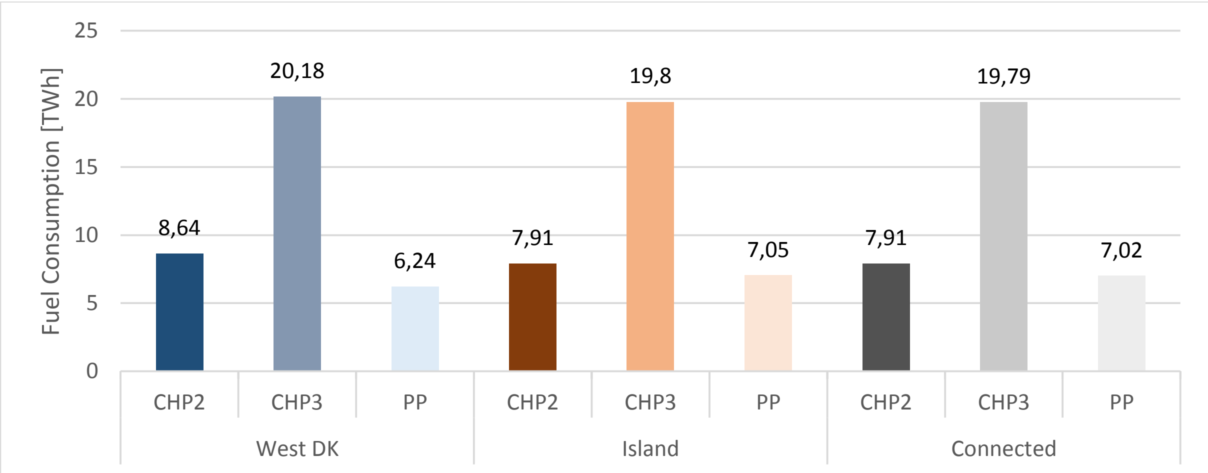

Figure 4. Fuel consumption for decentral CHP plant (CHP2), central CHP plant (CHP3) and power plants (PP), in the three models in analysis 1: single entity (West DK), regions as islands (Island), and interconnected regions (Connected)

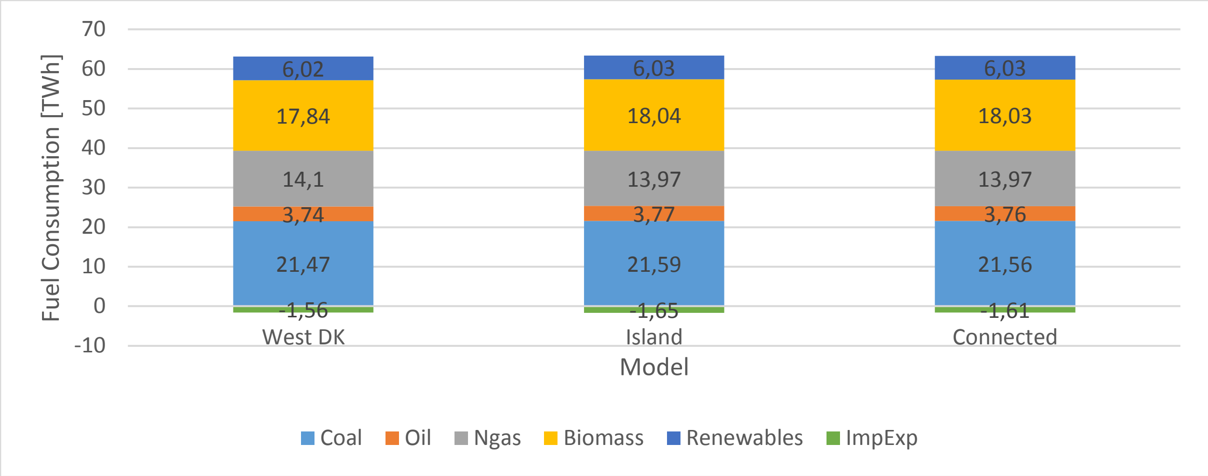

Figure 5. Net Total Fuel Use in the three models in analysis 1: single entity (West DK), regions as islands (Island), and interconnected regions (Connected)

Analysis 2: Smart Region development for Southern Region

Figure 6 and Figure 7 show respectively the fuel demand divided by primary electricity producer and the total fuel demand in the system. Figure 6 indicates once again that there is not a big difference between the three ways of modelling the energy system of Western Denmark. Best exemplified by comparing the single entity model with the regions operating in island mode. However, bigger differences can be seen here than in Analysis 1. First of all, due to the regional modelling it is possible to take in regional differences. Second, the Southern Denmark system is developed as a smart region according to the CEESA scenario, meaning that large amounts of wind turbines and combined cycle gas turbines are installed instead of steam turbine CHP, and heat demand is lowered, see Table 1 and Table 2. These new technologies changes the layout of importable and exportable electricity between the regions, which can be seen in Figure 8. More exportable electricity is available in situations where import is needed. This in spite of still having more or less same conditions in terms of wind, heat and electricity demands, and solar production. Overall the regional approach in this case leads to the most efficient system, when looking at fuel consumption, and least amount of fuel needed for pure electricity production, whereas the approach of modelling countries as a single entity results in the least amount of exportable electricity to surrounding energy systems.

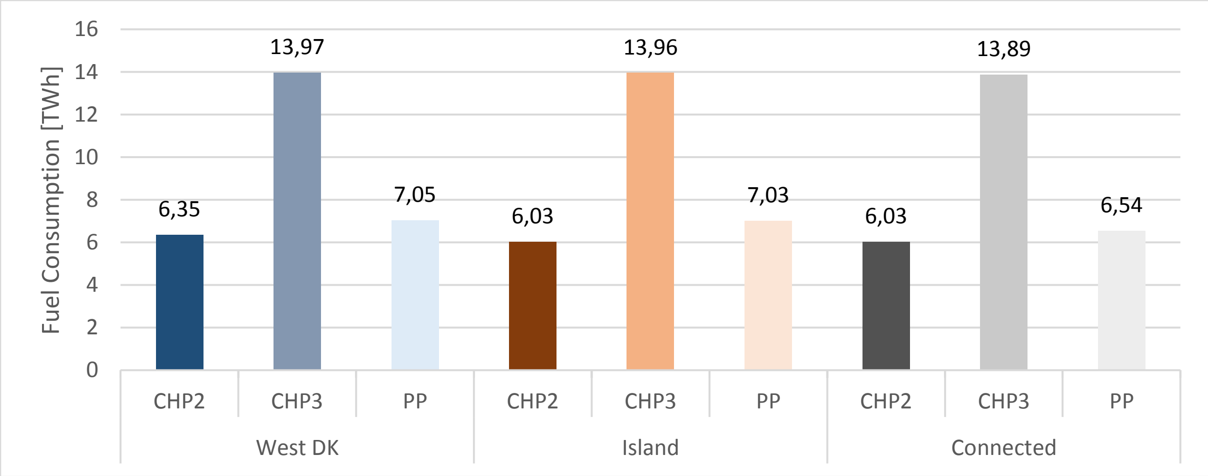

Figure 6. Fuel consumption for decentral CHP plant (CHP2), central CHP plant (CHP3) and power plants (PP), in the three models in analysis 2: single entity (West DK), regions as islands (Island), and interconnected regions (Connected)

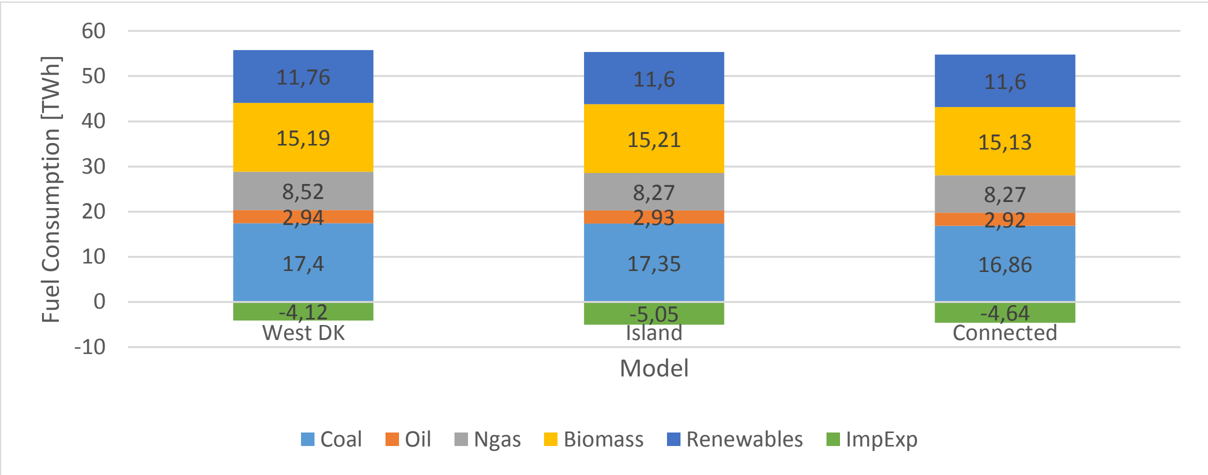

Figure 7. Net Total Fuel Use in the three models in analysis 2: single entity (West DK), regions as islands (Island), and interconnected regions (Connected)

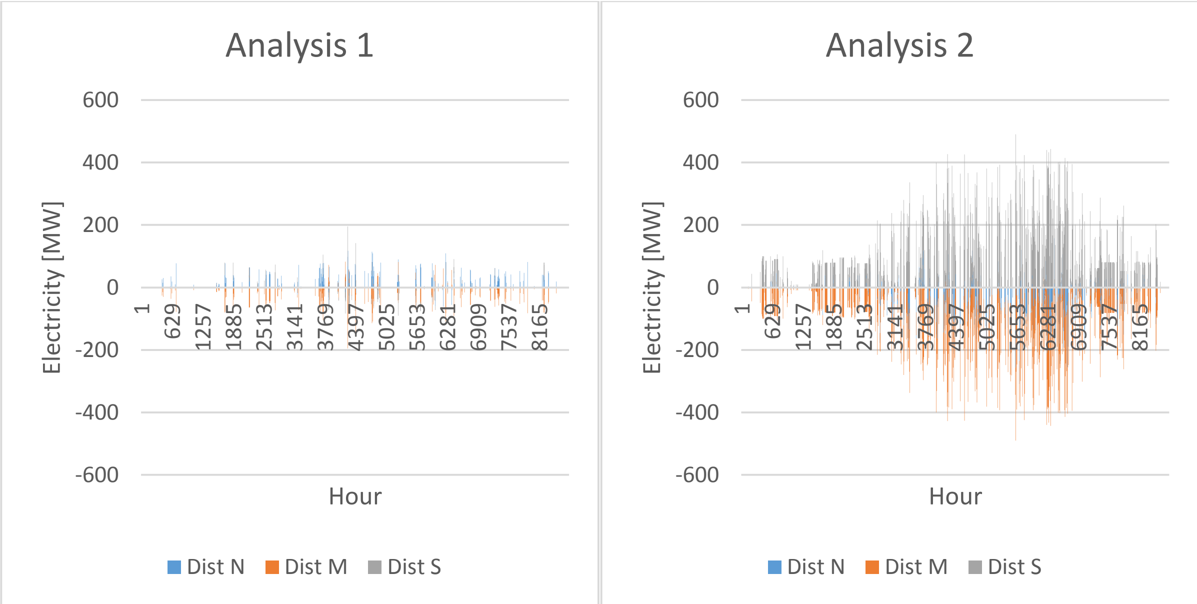

Figure 8. Hourly electricity exchange between the three regions, Northern (Dist N), Central (Dist M), Southern (Dist S). Positive number indicate export, while negative indicate import.

CONCLUSION

This study suggests a methodology for linking regional and national analyses through the usage of EnergyPLAN and the identification exportable electricity and import needs between the regions. Thus it becomes possible to analyse smart cities and regions in relation to the surrounding country. By applying the suggested methodology to the case of Western Denmark and a Smart Region development of the Southern part of Western Denmark, the consequences of the approach is identified. From the two analyses the following can be concluded.

The suggested methodology enables studies of smart regional development and can link such development to the remainder of the country as is shown in Analysis 2, where it is also seen that the methodology does utilize the interaction between the systems to improve the overall performance of Western Denmark. As such, the local developments have a national consequence.

What is seen from Analysis 1 is however, that such interaction is small when energy systems are very similar and the demand profiles are similar. There is almost no interaction, when systems are over-producing and under-producing in the same hours. There is no technical benefit of exchanging in these situations. Analysis 2 introduces a Smart Region, and due to the radical different energy system, more exchange is happening. However, in both analyses the differences are small between modelling in island mode, modelling with connection and modelling Western Denmark as a single entity. The final parameter not tested here is different demand profiles. Future studies should look into what consequences that could have for the suggested approach.

Overall, the tool enables regions to relate their Smart City plans to future national energy systems, but this study suggests small differences on overall national levels, why the tool has to be applied in cases where local planning is relevant.

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