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Abstract
The utilisation of fluctuating renewable energy sources is increasing world-wide; however, so is the concern about how to integrate these resources into the energy systems. The design of optimal energy resource mixes in climate change mitigation actions is a challenge faced in many places. This optimisation may be implemented according to economic objectives or with a focus on techno-operational aims and within these two main groupings, several different criteria may potentially be applied to the design process.

In this article, a series of optimisation criteria are reviewed and subsequently applied to an energy system model of Western Denmark in an analysis of how to use heat pumps for the integration of wind power.

The analyses demonstrate that the fact whether the system in question is modelled as operated in island mode or not has a large impact on the definition of the optimal wind power level. If energy savings and CO_2 emission reductions beyond the system boundary are not included in the analysis, then it is either not feasible to expand wind power to a high degree or it is conversely more feasible to install relocation technologies that can utilise any excess production. The analyses also demonstrate that different optimisation criteria render different optimal designs.

Key words
renewable energy integration, optimisation criteria, energy systems analyses, energy cities, energy islands

1. Introduction

Increasing attention is given to the abatement of climate change, to the societal costs of covering an ever growing energy need and to the security of supply in countries which, in many cases, rely on politically volatile regions for their energy supply. Due to these circumstances, cities, regions and countries focus on harnessing locally available renewable energy sources. Many geographic locations are hence in the process of making local energy plans with the aim of becoming renewable energy cities or renewable energy islands. This includes cities such as Frederikshavn, Denmark;

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Dardesheim, Germany, and Dong-Than in China, and islands like Samsø, Denmark, and Gotland, Sweden [1] but also, to a lesser extent, entire countries, of which e.g. Denmark has had ambitious renewable energy targets for a long time - see e.g. [2-4]. However, questions remain open: What is a renewable energy city? When can an area claim to have a sustainable energy supply? And how does one determine the optimal resource mix?

The transition from fossil fuel-based energy supplies to renewable energy supplies has a number of impacts on the energy system. With a few exceptions, such as bio-fuels and hydropower, most renewable energy sources are of a fluctuating nature and are, furthermore, of a "use it or lose it" character. In spite of these constraints, systems relying on e.g. wind power – whether small-scale wind-diesel hybrid systems or large-scale systems involving more types of productions and demand – still need to have the same load following capabilities as conventionally fuelled energy systems.

At a general level, such systems may be designed from an economic perspective or from a techno-operational perspective; but within these two pillars, several sub-divisions can be found. Economic optimisations criteria include e.g. total energy systems costs, capacity costs and societal costs. From a techno-operational perspective, optimisation criteria include fuel savings, CO_2 emissions, reserve/back-up capacity, required condensing mode power generation, minimisation of import/export, and elimination of excess power generation. All of these criteria can be applied to assess how well the system integrates renewable energy. In addition to these criteria, systems may be analysed in either island mode or as connected to surrounding areas. This opens up for new issues, such as whether or not CO_2 emission reductions realized in neighbouring areas, as a consequence of changes in the area in focus, should be credited this area.

Many scholars have treated the issue of integrating renewable energy sources into energy systems without compromising the load following capability of the system (see e.g. [5-17]). However, there is no generally accepted common design criterion according to which the systems are analysed, optimised and designed. This is also the case of different political institutions, which use different criteria when defining aims.

2. Scope of the article

This article reviews a number of possible optimisation criteria for the design of energy systems with large shares of fluctuating renewable energy sources. A selection of these criteria are applied to an analysis of Western Denmark. This is a region with a large penetration of wind power at approx 26 % in 2007 (based on hourly production and consumption data from [18]) and where wind power is expected to increase even further. Denmark is also a country with a large share of the heat demand being covered by district heating; generally produced on cogeneration of heat and power (CHP) plants giving rise to a district heat-tied electricity generation. A high wind penetration in combination with district heat-tied electricity generation makes the area very relevant for studies of integration of wind power. In the article, a model is thus set up detailing electricity and district heat demands, conventional thermal power plants, CHP plants, heat storages in connection with the CHP plants, wind turbines and foreign transmission connections. Based on this model, it is analysed how wind power can best be expanded from 20 per cent to 40 per cent of the demand, using heat pumps for integration. Heat pumps are not the only technology that may assist in the integration of wind power, however it is a moderately priced and energy efficient technology that already exist in large scale applications such as the Stockholm District Heating system. This is in contrast to costly electricity storage technologies based on e.g. vanadium redox batteries or based on hydrogen which in addition have poor cycle efficiencies. Technologies such as compressed air energy storages (CAES) have also yet to prove economically attractive as demonstrated by e.g. Lund & Salgi [19]. Heat pumps are a logical option due to the existence of CHP plants, district heating grids, and heat storages in Denmark. They give a very energy efficient downward regulation possibility by introducing an electricity demand while at the same time reducing the heat tied production on CHP plants. Their upwards regulating ability is restricted to when they are operating though.

3. Optimisation criteria

A wide range of criteria exist for the design of optimal energy systems configurations. In the following, a number of these are presented and deliberated. Within some fields, it is possible to determine a global extreme. This may e.g. apply to per-unit costs as a function of the production volume in a manufacturing industry where start-up costs are high and where additional labour or additional machinery will, at some point, be required. In between these two points, a global (or at least a local) minimum may be found. In contrast, when analysing e.g. the optimal expansion of wind power and using e.g. fuel use as an optimisation criteria, the fuel used is much more likely to approach a fixed level, more or less asymptotically. Without a clear extreme of the fuel use, in the case of installed wind capacity function, this cannot simply be used as an optimisation parameter. One could consider using the derivative and setting a limit to this. In the physical world, this would mean expanding wind power as long as the incremental expansion renders a positive effect on the fuel use beyond a certain threshold value.

However, while this would be an analytically quantifiable approach, it would not result in an objective identification of an optimal system design. A possibly better approach is to set up, analyse and compare alternatives. Methods such as the Diamond E (see [20]) can then be used to help identifying which requirements the system must meet and thereby help establishing relevant criteria.

While some articles focus on economic criteria and others focus on technical criteria, it is in practice difficult to make a clear distinction between these, as also deliberated in the following review of the criteria.

3.1. Reserve capacity requirement

From a technical point of view, reserve capacity (or backup capacity) requirement is a parameter used in e.g. [21] to assess how well a system integrates wind power. By using this parameter, the maximum required generating capacity should basically be minimized over a period of time, e.g. a year or more. The criteria may or may not take fault situations into consideration – so-called n-1 or n-2 in which one or more production units are unavailable. This, of course, adds to the required reserve capacity. However, this added reserve capacity should not necessarily be attributed to the circumstance that the analysed system is characterised by a large share of fluctuating renewable energy sources. The added reserve capacity is irrespective of the type of energy system. In fact, the replacement of one 300-MW unit in a thermal power plant by 100 3-MW wind turbines decreases the impact of a faulty unit. However, as n-1 or n-2 considerations deal with the most critical units – and hence any reserve capacity in renewable energy-based systems – any addition which they provide to the reserve capacity is typically irrespective of whether the system is an ordinary thermal system or a renewable energy-based system.

Explicitly or not, a strong relationship can be found between reserve capacity considerations and economic costs. The capacity naturally has a fixed cost which must be covered by the electricity consumers, regardless of the fact whether or not this capacity is used.

3.2. Use of import and export

Related to reserve capacity considerations is the use of import or export in securing a system's load following capability. Import and reserve capacity play similar roles in the energy system. Export from the system is not per se a positive or negative quality from a technical perspective, and is hence not directly convertible to a design optimisation criterion. Critical import/export – i.e. required import/export beyond the transmission line capacity – must of course be avoided. If not, then added transmission capacity must be considered. An example of analyses aimed at limiting the export of electricity is found in [2]. In the case of critical export, production units may also be shut down at the expense of the system's capability of exploiting available "use it or lose it" resources.

From an economic perspective, non-critical export may provide an income. However, if the export takes place at times when the given energy system is forced to export due to e.g. windy conditions and a lack of local integration capability, then the seller is in a poor bargaining position, as there is no alternative to transmitting the excess electricity beyond the system boundary. The same is naturally the case with import – though this is of course a potential expense.

3.3. Island mode, connected mode or connected island mode

The discussion of import/export opens up for the much wider discussion of whether or not the system shall (or shall be able to) operate in island mode, i.e. without relying on transmission capacity to and from the outside world. There are arguments in favour of the island mode approach, the connected approach and what may be coined "connected island mode", where the latter refers to a system which is connected to the outside world but in which the use of the inter-connector is avoided, if possible.

In favour of the island mode approach is the circumstance that while it is indeed possible to have large shares of e.g. fluctuating wind power in an energy system already with the present technologies, this is to a high degree due to the fact that the system can rely on the outside world in terms of balancing supply and demand. Analysing an area in island mode thus reveals more about the system's dynamics. Designing a system that may function in island mode may thus enable the system operators to make voluntary decisions on when to import and export, rather than being forced through external and non-controllable circumstances.

Whether or not a system is modelled as operated in island mode is also related to how credits are treated across boundaries. If energy saving and CO_2 emission reductions beyond the system boundary are not credited in the system – which is the case in e.g. the Nordic power pool NordPool – then it may either not be feasible to expand wind power to a high a degree or be conversely more feasible to install relocation technologies that can utilise any excess production.

For Western Denmark, the duration curve in Fig. 1 demonstrates the high reliance its wind power intensive system has on the ability to trade electricity with neighbouring countries. Wind power alone accounted for more than 100% of the electricity demand in this area for more than 50 hours of 2007, and during 1574 hours (18 percent of the time), the contribution was larger than 50%. With a large amount of district heating tied CHP electricity production, there are further restrictions on the energy system emphasising the fact that surrounding areas are used for balancing purposes in the current situation.

In a future situation in which such neighbouring regions may also exploit fluctuating energy sources, these regions will probably not have the flexibility to assist other regions in load balancing. Hence, in a future situation with extensive use of fluctuating renewable energy sources, the system may need to be, if not physically then virtually, split up into a number of self-reliant subsystems each with appropriate load following capabilities. The line of reasoning for opting to model and design self-reliant energy systems is not unlike Kant's Categorical Imperative [22] or Egner's Cardamom Law [23].

If the area in question is literally islanded, then this approach is of course also the relevant one.

The connected approach resembles the current Danish situation in which imbalances to some extent are remedied with the assistance of the balancing capabilities of surrounding areas. Or in other words, the problems are shared with the neighbours. As only few areas have high penetrations of fluctuating renewable energy sources, this approach is not a problem in most of today's systems. However, there may be economic issues to address, as noted under import/export.

Harnessing fluctuating renewable energy sources over a larger geographic area does offer some synergies in terms of evening out natural variability through spatial distribution, but the effects of this are limited [21].

Finally, the Connected island mode attempts to bridge the two former approaches by giving priority to the ability to operate in island mode – but also by including a certain possibility of exchange with the surroundings. The issue remains of course how to establish a limit of permissible exchange; is it only to be permitted in contingency situations; is it also permitted under non-contingency but still abnormal conditions, or is it even permitted as a daily occurrence.

3.4. Condensing mode operation

In energy systems with cogeneration of heat and power (CHP) plants, electricity generation on condensing mode power plants is usually avoided to the highest extent possible. An example of an analysis applying this methodology is [15]. While having higher electric efficiencies than back-pressure or extraction CHP plants, condensing mode power plants have far lower total efficiencies, as substantial amounts of waste heat are discarded. Regardless of whether the system is exploiting CHP plants or not, fuel use is to be minimised. In non-CHP systems, however, a more immediate relationship is found between fluctuating renewable energy input and fuel savings on condensing mode power plants. In systems with CHP, the optimisation process offers more possibilities, such as the appropriate use of heat storages and the scheduling of the CHP plants. There is, hence, not a simple correlation between fluctuating renewable energy input and fuel savings in such systems. The impact is determined by the system's configuration and the choice of regulation strategy, making condensing mode operation an interesting performance indicator.

3.5. Primary energy consumption / Fuel use

Rather than focusing on condensing mode power generation and the fuel savings that may be achieved through the minimisation of this, a wider approach is simply to look at the primary energy consumption (PEC) of the energy system in question. The issue of import/export plays a role here. Should the system in question be credited fuel savings beyond the system boundary caused by the export of e.g. electricity, district heating or other energy carriers produced within the system? Should the system be debited import of these – and how should the fuel equivalence be assessed? Focusing on electricity, one way would be to assume that the alternative to import/export would be running the marginal production facility more or less. This would typically be a condensing mode power plant. It may be argued that the marginal production in complex systems with many production technologies, energy carriers and interdependencies is not always clearly identified as it may neither be the same in all hours of the year nor the same under all operating conditions.

Thus, the applicability of using a marginal production facility to compensate for import/export has its limits. Export is typically only relevant when the condensing mode power plants cannot be down-regulated any further, in which case the condensing mode power plants are not an option and thus do not represent the marginal production facility. Likewise, import would also typically be given second priority to production within the system, which means that import would only occur when the required production exceeds the available capacity of the system. The condensing mode power plant would not be the correct marginal facility in this case, either. A different application of the methodology would be to use the marginal production facility in the neighbouring country/area in the same way as the system-internal marginal production facility was used.

Other energy carriers may be treated in a similar way as electricity, with e.g. a boiler for district heating, an electrolyser for hydrogen, etc. Of course, some of the same issues as outlined for electricity are relevant here, as well.

Contemplating fuel use, it may be considered to focus a) solely on actual physical fuels, as suggested by the term “fuel use”; b) solely on non-renewable fuels, or c) on all energy sources including wind, solar, wave, etc. This is demonstrated in Figure 2, in which it is noticed that waste is indicated as a renewable as well as a non-renewable source. It could be argued that waste is renewable on the grounds that, despite the fact that a large proportion derives from fossil fuels, the marginal effect of combusting e.g. plastic produced on the basis of hydrocarbons is nil if decomposition in nature is the alternative. This process is very slow, though.

According to OECD, IEA and Eurostat methodology, waste is considered partly renewable and, as such, should be distributed according to the biodegradable / non-biodegradable fractions, see [24].

Also according to OECD, IEA and Eurostat methodology, nuclear is accounted for in terms of fuel equivalence, assuming that it is produced at a power plant with an electric efficiency of 33%, whereas the fuel equivalence of e.g. wind power is calculated using an efficiency of 100%. Using this methodology, thus gives a lower primary energy consumption for systems with wind power than for systems with nuclear power.

3.6. Renewable energy shares

Measuring the renewable energy share of the energy consumption is yet a fuel-accounting criterion. Again, it must be settled how to account for import/export of energy carriers. It is also important how non-fuel renewable energy sources are converted to fuel equivalence. One may argue that the previously described OECD, IEA and Eurostat methodology makes energy systems with substantial renewable energy sources, like wind power, appear more favourable compared to conventionally fuelled energy systems; however, the methodology tends to hide such energy sources when renewable energy shares are calculated. Table 1 shows the effect of applying the OECD methodology to a simple system with 20 TWh of wind power and 80 TWh of nuclear power.

Clearly, the Primary Energy Consumption is lower with the OECD methodology, but the renewable energy fraction appears more favourable when wind power is modelled as e.g. nuclear power.

To complicate matters further, renewable energy shares may also be calculated in terms of final energy consumption. Using the same efficiencies as in Table 1 in a system with only electricity consumption in fact corresponds to using final energy consumption. However, this is an exceptional case.

A newly defined European Union goal of achieving 20% renewable energy coverage of the energy demand relates to final energy consumption [25], whereas e.g. national Danish statistics include the losses in the energy transformation sector [26] and thus refer to primary energy consumption.

The burden of meeting a certain requirement is generally reduced when applied to final energy consumption rather than to primary energy consumption. If the renewable energy sources have higher losses through the transformation system, the burden is not reduced. If the fuel equivalence of solar cells is calculated using an actual physical efficiency of e.g. 10 %, they will constitute a much higher production in terms of primary energy consumption than in terms of final energy consumption. However, as the fuel equivalence of wind power, solar cells and some other electricity producing technologies is typically modelled as being identical to the electricity production, according to OECD, IEA and Eurostat methodology, this is most often not the case.

The burden of meeting specific targets will therefore also be reduced more for countries with inefficient transformation systems than for countries with more efficient transformation systems, when adapting a goal related to final rather than primary energy consumption.

3.7. Carbon dioxide emissions

Optimising the design by quantifying – and minimising – carbon dioxide emissions is a success parameter used in many national energy plans, as a consequence of the work in the United Nations Framework Convention on Climate Change and the country-specific targets lined up in the Kyoto Protocol ([27]). Carbon dioxide emissions are closely linked to the fuel use considered previously with the distinction that different fuels have different carbon dioxide emission factors. Thus, where primary energy consumption was neutral to the fact whether fuels were high emission fuels, like lignite, or low emission fuels, like natural gas, biomass or even nuclear, the distribution of fuels is important here.

The considerations pertaining to import and export are clearly relevant for carbon dioxide emissions, too. This has, in fact, proved to be an obstacle in the internal European Union re-distribution of Kyoto Protocol requirements. Countries like Denmark have unsuccessfully advocated that the base-year should be corrected for international electricity trade and for climatic deviations from the long-term average, which affects the demand for space heating.

Related to carbon dioxide emissions are newer concepts such as carbon footprints – see e.g. [28]. In the simplest form, the carbon footprint merely corresponds to the carbon dioxide emissions of a given area or activity, but it may also be based on a life cycle assessment (LCA), thus including emissions throughout the life cycle of the energy system in question, involving e.g. construction, demolishment, growing of energy crops, and the production of fertilisers for energy crops. LCA is also used in its own right to assess energy technologies as exemplified by [29]. The LCA Carbon footprint methodology is also applied to non-energy products – e.g. [30], thereby providing a common frame for environmental impact assessments. The Ecological footprint (see e.g. [31-33]) adopts another approach and determines the land area required to sustain a certain activity. Thus, it gives an indication of sustainability through a comparison of the required land area to the actual land use or the available land area.

3.8. Economic costs

Economic cost evaluation is a main parameter for assessing the feasibility of a given energy system configuration. However, "economic costs" is also a term with ample latitude for interpretation. As demonstrated by Integrated Resource Planning (IRP) (see [34] for one of the first journal references to this planning methodology), several types of economic costs can be defined, including

- Societal costs –also including e.g. external costs and benefits,
- utility costs – determining the costs incurred by the energy companies,
- rate impact – determining the cost of each unit of e.g. electricity, and
- total resources – determining all incurred costs.

For the sake of completeness, a last parameter in IRP is Participant Costs, which quantifies benefits for consumers engaged in Demand Side Management (DSM) projects. However, this parameter is too specific for the aim of this article.

One common feature for most economic criteria is the fact that the costs can be determined as net present values, annual costs, or levelised annual costs.

3.9. Societal costs

An important element in IRP is the analysis of how different actors are influenced by given measures. This is also seen in the list of costs, in which each cost criterion focuses on the costs for a distinct target group. Hence, in IRP, a given measure should prove beneficial according to all of the above parameters, though in effect, this is rarely possible. For this reason, societal costs are typically used as the measuring gauge in IRP work as exemplified by [35]. However, societal costs are also used beyond formal IRP, as exemplified by [2] who applies these costs as a parameter for the optimisation of energy systems. While the term Societal costs relatively easily may be defined as "all cost to the society", this is, in practise, more complicated for boundary reasons. From the simplest point of departure, the societal cost of a given good might be approximated as market price excluding taxes, but progressively more ambitious definitions may include more and more elements. Environmental externalities may e.g. be added and the analysis may be conducted using import values. This is particularly the case in situations of unemployment, where it may be argued that domestic labour costs for the society are zero if the labourers in question would not otherwise be contributing to the wealth of the society.

3.10. Cost of Energy, Utility Costs and the Rate Impact

Utility costs adopt, as the term suggests, a much more confined business economic approach. Apart from the case of formal IRP, this term is not applied broadly. Related to the utility costs is, however, the Cost of Energy (CoE), which is used broadly by e.g. [36-38]. This parameter determines the cost per unit of energy whether being electricity, district heating, natural gas, hydrogen, etc. It is, thus, also closely related to the Rate impact, with the main difference lying in the application. The Cost of Energy is often applied to simple systems – e.g. the cost of producing one kWh on a given solar cell panel, on a given fuel cell or in a given wind diesel hybrid system. The rate impact is typically more holistic as it determines how the energy price for consumers is affected. As consumers are supplied by systems of varying complexity, more factors and a system-oriented approach are hence required to determine the rate impact than in the case of the simple Cost of Energy of a single technology.

The Cost of Energy is also referred to as the Levelised Cost of Energy (LCE) or Levelised Unit Electricity Cost (LUEC), as in [39]. Both of these terms emphasize the fact that the cost is determined over a certain time horizon – e.g. the life time of the specific technology. In practise, the objective it is a matter of *"finding the price that sets the sum of all future discounted cash flows (net present value, or NPV) to zero"*, as phrased by Ayres et al [39].

3.11. Total Resources

Total resources in IRP terminology refer to resources spent by consumers, energy companies and government bodies (e.g. as subsidies) alike. They are not to be confused with societal costs, as societal costs also include costs without a direct market value that hence need to be monetized beyond the market system.

3.12. Marginal costs

Closely related to optimisation criteria are long-term marginal costs and short-term marginal costs (sometimes referred to as short-run marginal cost and long-run marginal cost). Here, the cost of producing (or consuming) one extra unit of energy is calculated (short-term marginal cost) or the cost of producing (or consuming) one extra unit of energy including capacity expansion/renewal is calculated (long-term marginal cost). But as applied in e.g. [40], this may rather be used to check for economic sustainability by comparing these unit costs to the unit cost of energy for consumers.

4. Application of the criteria to a test case

The various criteria detailed in the previous sections are tested in an analysis with the objective of determining the appropriate level of heat pumps needed to assist the integration of wind power in the Western Danish energy system.

4. 1. Energy system scenario for Western Denmark

Denmark is separated into two non-connected electricity systems (many more if counting in Greenland and the Faeroe Islands). These analyses focus on the continental Western Danish system. The analyses are based on an energy system scenario for the year 2020 created by a working group established by the Danish Energy Authority ([41,42]. The same scenario has been used in modified forms in e.g. [15,17] for analyses of the integration of wind power. The main parameters of this scenario are presented in Table 2.

In addition to the production plants, the CHP plants are also combined with heat storage with a capacity of 10 GWh, corresponding to roughly 4 hours of average heat demand.

The conversion efficiencies – relevant for the analyses including fuel usage – are as listed in Table 3.

The fuels for the system are a mixture of coal, natural gas, oil and biomass (See Table 4). Biomass is used on all electricity producing plants and in non-CHP district heating. Oil is used only for boilers. Note that boilers are also used at the CHP plants during peak load periods or when electricity demand/prices are too low to warrant CHP operation.

Note that energy consumption for transport is not included in the analyses.

Fuel costs are as listed in Table 5. Notice that compared to 2008 world market prices, costs are fairly low. A world market crude oil price of e.g. 100 US$ per barrel corresponds to approximately 11 €/GJ; however, in order to make the analyses consistent with the scenario, the low fuel price is used.

For the analyses in which electricity trade to the outside world is permitted, a synthetic electricity spot market price variation with an average price of 225 DKK/MWh (30.2 €/MWh) is used. This has been the average Nord Pool spot market price for Western Denmark for the years 2000 to 2007, according to Nord Pool [43].

Besides fuel costs, some fuel handling, operation and maintenance costs are included in the analyses. Taxes are also applied where required. These are based on scenario work by Lund & Mathiesen [44]. Taxes are also included to determine Total Resources, as this is a business economic cost.

The only investment cost that is included in the analyses is that of heat pumps. Costs of large-scale heat pumps using ambient temperature heat sources are, according to [45], in the range from 0.6 to 1.3 M€ per MW_{th}. In this article, a cost of 1 M€ per MW_{th} is used, corresponding to 3 M€ per MW_e.

The heat pumps are modelled with a COP (coefficient of performance) of 3.0 and they are assumed to have this COP at the required flow temperature level. In other words, no boilers are applied to raise the flow temperature.

The costs of the remainder of the system are not included. This of course means that it is not possible to determine the production costs of electricity and heat; only the marginal effect of heat pumps on the economy is assessed.

All the parameters in Tables 2-5 remain constant throughout all analyses, and only heat pumps are varied in size in order to analyse how they affect the integration of wind power into such a system.

4.2. The energy systems analyses model

The system is modelled using the EnergyPLAN model, which is a model developed particularly with the intention to enable hour-by-hour analyses of energy systems with many interdependencies (see Figure 3) and with many fluctuating energy sources. EnergyPLAN is hence appropriate for analysing future energy systems in which the integration of fluctuating energy sources becomes a main issue.

The model is a deterministic model based on hourly distributions of energy sources and energy demands – mainly electricity and heat demands – for a one year period. The model applies a sequence of priority to the production technologies. Top priority is given "use it or lose it"-productions like wind power, photo voltaic cells, wave power, solar collectors and to some extent geothermal power production. Then comes technologies that traditionally follow a set schedule such as industrial cogeneration or waste incineration, where industrial cogeneration follow the requirements of the industry and waste incineration typically is operated at nominal load to ensure optimal combustion for environmental reasons. Then come CHP plants for district heating, where the model determines their operation within the limits given by the heat demand and the contents of heat storages. Lastly come condensing mode power plants for electricity generation and boilers for district heat generation that are added as the last and most energy inefficient resort.

In addition to heat pumps and heat storages, the model also handles electricity storages such as pumped hydro storages, battery storages, CAES, electric vehicles, and hydrogen systems. If stipulated, these and others may add flexibility to the system and thereby provide a possibility for ensuring the balance between electricity production and demand.

One of the cornerstones of the model is its ability to model different regulation strategies. In actual systems, CHP plants may e.g. be operated with the single purpose of following the heat load, according to a triple electricity tariff, or in order to facilitate the integration of fluctuating renewable energy sources by utilising heat storage and heat pumps for temporal load shifting. In these analyses, the latter of these regulation strategies is applied, as focus is placed on the best possible integration of renewable energy.

The EnergyPLAN model ensures that the operation of the electricity system is within the certain boundaries in order to ensure system stability. It will not permit production based on asynchronous generators to cover too much of the hourly electricity demand, as these are not able to supply ancillary services - see e.g. [15].

Apart from technical analyses of how to design systems capable of integrating fluctuating energy sources, the model is also able to perform certain economic calculations involving e.g. income from selling electricity beyond the system boundary.

The model is further described by its creator Henrik Lund in e.g. [8,46].

4.3. Energy systems analyses

As mentioned previously, it is not always possible to find a specific mathematical optimum when designing energy systems. Thus, three different levels of installed heat pump capacities are modelled to analyse their impact on the various optimisation criteria. Heat pumps are modelled in levels of 200, 400 and 600 MW_e installed capacity, respectively. In addition to these levels, a reference case is included with no heat pump capacity installed. This reference is mainly used to determine the Rate Impact.

As deliberated in the previous section, it is of large importance whether or not the system is permitted to interact with the surroundings – both from a technical perspective regarding the utilisation of import and export for balancing purposes, and from an economic level e.g. regarding the value of export to the system. The analyses are thus separated into these two main cases.

Total resources are calculated as socioeconomic costs with the addition of taxes on fuels and electricity for district heating, power plant and individual use. Non-utility commercial consumers of energy are not taxed. Hence, only the domestic use of electricity is taxed. This is estimated at 31% of the total electricity demand, based on 2006 data [47]. Electricity for heat pumps is taxed separately. VAT is added to all costs, irrespective of the type of consumer, at the Danish flat rate of 25%.

In the specific Scandinavian context, a so-called bottleneck cost or income is introduced, when required interconnection capacity supersedes installed interconnection capacity. This is not included in the analyses.

Energy systems analyses of the system run in island mode generate the results listed in Table 6; and for the connected mode, the results are listed in Table 7 for a number of the main optimisation criteria deliberated.

The most favourable technical design varies according to the optimisation criteria applied, as indicated by the shading in Tables 6 and 7, both in the interconnected mode and in the island mode. It also varies with the same criterion, when comparing island mode with connected mode. Hence, no unequivocal best design can be defined; i.e. one design that is optimal according to all the optimisation criteria. In addition to this, a few comments should be attached to some of the results.

In general, the higher the share of heat pumps, the better within the range analysed. Some optimisation criteria show a different profile, though. Condensing mode operation increases e.g. with the share of heat pumps. This could be attributed to the circumstance that added heat pump capacity increases the utilisation of wind turbines. However, present wind turbines are not able to supply ancillary services [15]; which means that added wind utilisation requires additional power plant operation in order to secure that ancillary services are supplied in a correct proportion.

Societal costs are lowered through the expansion of heat pumps, while total resource costs are increasing with higher heat pump capacity. The business economic decline is due to high taxes imposed on electricity for heat production. Thus, the results can also be used to show that there is a distorted tax incentive giving suboptimal solutions seen from a socioeconomic perspective.

In the island mode, there is an optimal sizing of heat pumps within the 200-600 MW_e range analysed for one of the criteria, whereas this is not the case for the connected mode.

4.4 Multi-criteria decision analysis

As the analysed case demonstrates, no uniquely best option can be identified, as the various optimisation criteria to some extent have conflicting outcomes. Decision-makers facing the task of choosing one energy system rather than another are thus faced with the choice between the different optimisation criteria. Through the choice of one optimisation criterion, the decision-maker sets the stage and thereby favours some options rather than others. In actual decision processes, one optimisation criterion is seldom used as a single decision criterion. Introducing more decision criteria gives a better understanding of the actual decision process but also induces a complexity that needs to be handled in an appropriate way.

Multi-criteria decision analysis (MCDA) is a method for incorporating multiple decision criteria into a framework for decision-making, and an extensive literature on the matter exists [48-52]. As phrased by Cavallaro and Ciraolo, "*The strength of the multi-criteria analysis lies in its ability to simultaneously evaluate a number of alternatives in relation to a multiplicity of viewpoints and to produce results that take into consideration any eventual tradeoffs between the values examined.*" [48] MCDA is not a uniquely defined methodology, though. There is a multitude of MCDA methodologies [49,51] which may generally be classified as

- Value measurement methods

- Goal, aspiration and reference level models,
- Outranking models [51,53]

In fact, as Løken concludes, *"Choosing among all the MCDA methods that exist can be said to be a multicriteria problem."* [51]. Only the first – the value measurements class and more specifically the multi attribute value theory (MAVT) – will be treated here, as an example of how to apply MCDA to energy planning optimisation problems. For an extensive literature review of other MCDA methods applicable in energy planning, see [51].

In MAVT, a series of decision criteria are chosen. For each criterion, the potential numerical range of the results must be normalised to a common scale in order to become comparable to the other criteria. Each criterion is assigned a subjectively established weight. The overall score of a given alternative is simply the sum of the products of decision criteria weights and normalised decision criteria values. Different alternatives may then be compared using this sum or value score.

However, while simple in math and principle, there is ample latitude for affecting the outcome of MAVT through the assignment of weights and through the normalisation of the decision criteria. Both are based on subjective decisions, but it may be argued that MAVT is a system that, at least, structures the subjectivity. Clearly, the weight assigned to e.g. carbon dioxide emissions is a choice, but so is the normalisation. Is the optimal value zero or perhaps a more realistically attainable target and how is the other end of the range established? The same issues are faced in life cycle assessments (LCA), but here, international norms and standards for normalisation have been established. It cannot be expected, however, that decision-makers would resort to internationally established standards for decision-making; a matter that by its very political nature is subjective.

4.5 Applying the MAVT to the analysed case

This example is based on the analysis of the islanded system. Priority has been given to Primary Energy Consumption (PEC), renewable energy shares, carbon dioxide emission as well as to economic costs; whereas operational parameters, such as condensing mode operation and reserve capacity requirement, are disregarded. Condensing mode operation is indirectly addressed through the Primary Energy Consumption (PEC). The criteria weights and the parameters used in the normalisation are listed in Table 8.

Results of the analyses are listed in Table 9, in which it is seen that the 600 MW_e heat pump alternative has the highest MAVT score, indicating that this alternative fulfils the objectives better than the lower heat pump alternatives. However, while the MAVT score points at the 600 MW_e heat pump alternative, it is also very sensitive to the assignment of criteria weights and to the normalisation parameters. In general, the more the technical criteria are emphasised, the more will the MAVT score point at the 600 MW_e heat pump alternative. Conversely, if more emphasis is placed on economic criteria, then the 200 and 400 MW_e heat pump alternatives may reach the highest MAVT scores.

4.6. Error analysis and validation of results

The numerical modelling has been performed using the EnergyPLAN model, which has been used in a number of peer-reviewed articles including [5,8,11,15,21,44,54]. The model is thus well documented in literature and is furthermore under continuous development based on feedback from the energy planning community applying the model.

The objective of this article is to review a series of optimisation criteria and apply these to a case in order to demonstrate that different design criteria will give differing results. The numerical results of the actual system modelling are not the primary outcomes of the article and, in fact, any divergence between these numerical results only stresses the importance of defining success criteria very explicitly.

5. Conclusion

Many different optimization criteria might be applied to the design of environmentally benign energy systems. This article has deliberated a variety of these and has applied these to a case. The case analyses are based on a comprehensive energy system description. The system has been modelled in a tool tailor-made to investigate how energy systems may be designed to achieve the optimal integration of fluctuating energy sources. The question asked, however, was a fairly simple question regarding the selection between three well-defined cases; and, in spite of the simplicity of the question asked, the different optimisation criteria rendered different results. While multi-criteria analyses may better reflect the diversity of considerations faced by decision-makers by taking several criteria into account, the methodology still requires the user to be able to quantify preferences by assigning weights to different criteria and establishing a procedure for the normalisation.

This circumstance underlines the fact that no unequivocal answer can be found to the question of how to design an optimal energy system. Furthermore, the analysis shows that, when references are being made to specific renewable energy targets or to cities or areas with policy ambitions of changing to renewable energy or becoming carbon dioxide neutral, the optimisation criteria need to be clearly defined.

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References

Figure Captions

Figure 1: Duration curve of wind power's relative contribution to the electricity demand in Western Denmark 2007. Compiled on the basis of data from [18]**.**

Figure 2: Energy source vs fuel use vs non-RE fuel use.

Figure 3: Energy system outline in the EnergyPLAN model. Front page view of the model downloadable from energy.plan.aau.dk

Table captions

Table 1: Renewable energy share determination.

Table 2: Energy system scenario parameters.

Table 3: Efficiencies of the modelled system. The efficiencies for dwellings not connected to district heating networks vary depending on fuel; with the lowest efficiency for biomass boilers and the highest for natural gas boilers.

Table 4: Distribution of fuels used in the energy system. Biomass is given as a fixed available quantity per year, whereas the other fuels are variable and are given as fractions of the non-biomass fuel use. The only exception is individual and industrial use, which is included as fixed amounts of coal, oil and natural gas.

Table 5: Fuel costs used in the analyses. A Euro – DKK (Danish Kroner) exchange rate of 7.46 is used.

Table 6: Optimisation criteria for the energy system modelled in island mode. The shaded fields indicate the optimal installed heat pump capacity for each optimisation criteria. Rate impacts are relative to the reference (0 MW HP).

Table 7: Optimisation criteria for the energy system modelled in connected mode with 1700 MW interconnection capacity. The shaded fields indicate the optimal installed heat pump capacity for each optimisation criterion. Rate impacts are relative to the reference (0 MW HP)

Table 8: Applied normalisation and criteria weights for multi-criteria decision analysis

Table 9: MAVT scores for the three alternatives and the reference analysed in island mode. "Value" is the actual criteria value. "Normal." is the criteria value normalised to a range from 0 to 100. "N*W" is the normalised value multiplied by the criteria weight.

Table 1

	OECD methodology	Wind modelled as nuclear
Renewable energy share	7.7 per cent	20.0 per cent
Primary Energy Consumption	260 TWh	300 TWh

Table 2

Consumption [TWh]		Generating capacity [MW]	
24.87	Electricity	1450	Small-scale CHP
21.21	CHP District heating	1300	Large-scale CHP
3.50	Boiler district heating heat	Unlimited	Power plants in condensing mode
		2500	Wind onshore
		1445	Wind offshore

Table 3

	Electric efficiency	Heat efficiency
Individual heat	-	70% to 90%
Boiler DH	-	88%
Small CHP	38%	49%
- boiler	-	90%
Large CHP	39%	47%
- boiler	-	90%
Condensing	50%	-

Table 4

	Coal [% of fossil or TWh]	Oil [% of fossil or TWh]	Natural Gas [% of fossil or TWh]	Biomass [TWh/year]
Industry	1.97 TWh	8.86 TWh	5.19 TWh	0.56
Individual heat	0	3.64 TWh	4.99 TWh	3.10
Boiler DH	0	100%	0	1.46
Small CHP	0	0	100%	4.64
- boiler	0	100%	0	0
Large CHP	45%	0	55%	1.85
- boiler	0	100%	0	0
Condensing	45%	0	55%	0.62

Table 5

	Coal	Oil	Natural Gas	Biomass
DKK/GJ	14	26	30	22
€/GJ	1.88	3.49	4.02	-

Table 6

Criteria	0 MW_e HP	200 MW_e HP	400 MW_e HP	600 MW_e HP
Reserve capacity requirement	2635 MW	2709 MW	2709 MW	2709 MW
Use of import and export - peak	-/-	-/-	-/-	-/-
Use of import and export - average	-/-	-/-	-/-	-/-
Condensing mode operation	4.00 TWh/year	4.22 TWh/year	4.27 TWh/Year	4.28 TWh/year
Primary energy consumption (PEC)	88.78 TWh/year	87.37 TWh/year	86.66 TWh/year	86.24 TWh/year
- PEC corrected for import/export	88.78 TWh/year	87.37 TWh/year	86.66 TWh/year	86.24 TWh/year
Renewable energy shares (of PEC)	29.2%	29.6%	29.9%	30.0%
Carbon dioxide emissions (CO_2)	15.87 MT	15.45 MT	15.23 MT	15.10 MT
- CO_2 corrected for import/export	15.87 MT	15.45 MT	15.23 MT	15.10 MT
Societal costs (annual)	11748 MDKK 1575 M€	11607 MDKK 1556 M€	11604 MDKK 1555 M€	11663 MDKK 1563 M€
Rate Impact (Societal)	-	-5.66 DKK/MWh	-5.79 DKK/MWh	-3.42 DKK/MWh
Total Resources (business economic)	24503 MDKK 3285 M€	24756 MDKK 3319 M€	24990 MDKK 3350 M€	25476 MDKK 3415 M€
Rate impact (business economic)	-	10.05 DKK/MWh	19.46 DKK/MWh	39.00 DKK/MWh

Table 7

Criteria	0 MW_e HP	200 MW_e HP	400 MW_e HP	600 MW_e HP
Reserve capacity requirement	2707 MW	2988 MW	2988 MW	2988 MW
Use of import/export – peak	0/1700 MW	7/1700 MW	7/1700 MW	7/1700 MW
Use of import/export – average	0/307 MW	0/267 MW	0/238 MW	0/230 MW
Condensing mode operation	5.15 TWh/year	6.19 TWh/year	6.78 TWh/year	7.47 TWh/year
Primary energy consumption (PEC)	90.47 TWh/year	88.35 TWh/year	86.89 TWh/year	86.20 TWh/year
- PEC corrected for import/export	85.05 TWh/year	83.60 TWh/year	82.62 TWh/year	82.05 TWh/year
Renewable energy shares (of PEC)	27.0%	27.6%	28.01%	28.3%
Carbon dioxide emissions (CO_2)	16.73 MT	16.20 MT	15.85 MT	15.71 MT
- CO_2 corrected for import/export	15.42 MT	15.05 MT	14.82 MT	14.71 MT
Societal costs (annual)	12242 MDKK 1641 M€	11909 MDKK 1596 M€	11738 MDKK 1573 M€	11685 MDKK 1566 M€
Rate Impact (societal)	-	-13.38 DKK/MWh -1.79 €/MWh	-20.26 DKK/MWh -2.71 €/MWh	-22.40 DKK/MWh -3.00 €/MWh
Total Resources (Business economic)	25330 MDKK 3395 M€	25499 MDKK 3418 M€	25664 MDKK 3440 M€	25871 MDKK 3468 M€
Rate impact (business economic)	-	6.79 DKK/MWh 0.91 €/MWh	13.42 DKK/MWh 1.80 €/MWh	21.75 DKK/MWh 2.92 €/MWh

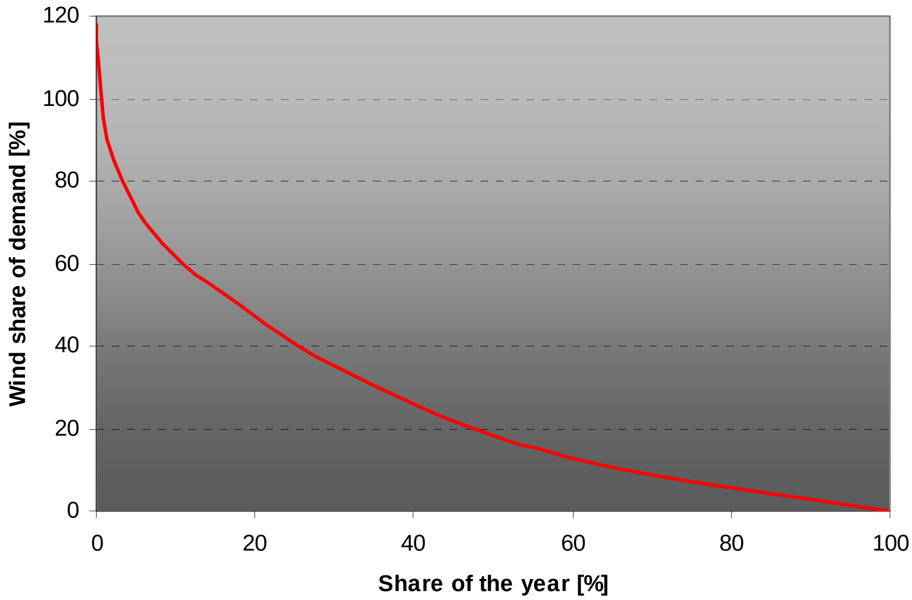
Table 8

	Range of criteria values			Criteria weight
	Best	Worst	Unit	[%]
Reserve capacity requirement	0	3000	[MW]	0
Condensing mode operation	0	5	[TWh]	0
PEC	50	100	[TWh]	20
RE Share	50	0	[%]	20
Carbon dioxide emissions	0	20	[MT]	30
Societal costs	0	2000	[M€]	20
Total resources	0	4000	[M€]	10

Table 9

	Reference			200 MW			400 MW			600 MW		
	Value	Normal.	N*W	Value	Normal.	N*W	Value	Normal.	N*W	Value	Normal.	N*W
	[actual]	[0-100]		[actual]	[0-100]		[actual]	[0-100]	0	[actual]	[0-100]	
Reserve capacity requirement	2635	12.2	0.00	2709	9.7	0.00	2709	9.7	0.00	2709	9.7	0.00
Condensing mode operation	4	20.0	0.00	4.22	15.6	0.00	4.27	14.6	0.00	4.28	14.4	0.00
PEC	88.78	22.4	4.49	87.37	25.3	5.05	86.66	26.7	5.34	86.24	27.5	5.50
RE Share	29.2	58.4	11.68	29.6	59.2	11.84	29.9	59.8	11.96	30	60.0	12.00
Carbon dioxide emissions	15.87	20.7	6.20	15.45	22.8	6.83	15.23	23.9	7.16	15.1	24.5	7.35
Societal costs	1575	21.3	4.25	1556	22.2	4.44	1555	22.3	4.45	1563	21.9	4.37
Total resources	3285	17.9	1.79	3319	17.0	1.70	3350	16.3	1.63	3415	14.6	1.46
MAVT Score			28.40			29.86			30.53			30.69

Figure 1



Wind share of demand [%]
120
100
80
60
40
20
0
0
20
40
60
80
100
Share of the year [%]

Figure 2

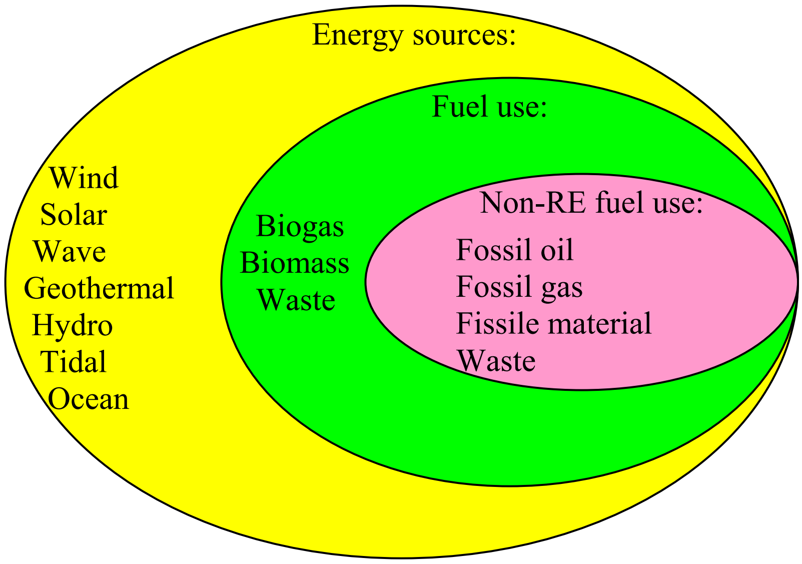
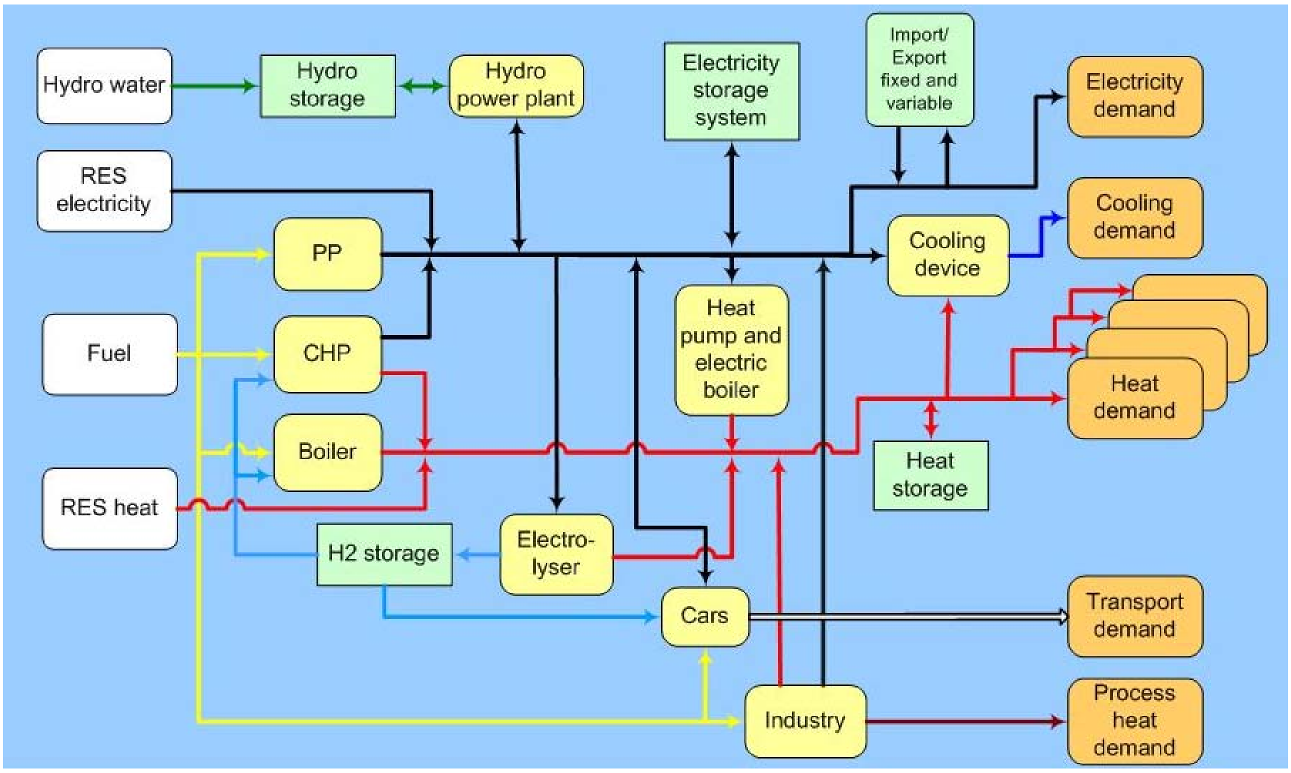

Energy sources:
Fuel use:
Non-RE fuel use:
Wind
Solar
Wave
Geothermal
Hydro
Tidal
Ocean
Biogas
Biomass
Waste
Fossil oil
Fossil gas
Fissile material
Waste

Figure 3


Hydro water
Hydro storage
Hydro power plant
Electricity storage system
Import/ Export fixed and variable
Electricity demand
RES electricity
PP
Cooling device
Cooling demand
Fuel
CHP
Heat pump and electric boiler
Heat demand
Boiler
Heat storage
RES heat
H2 storage
Electro-lyser
Cars
Transport demand
Industry
Process heat demand

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