Management of Fluctuations in Wind Power and CHP Comparing Two Possible Danish Strategies

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Received 17 November 2000

Abstract

Both CHP (Combined Heat and Power Production) and Wind Power are important elements of Danish Energy Policy. Today, approximately 50% of both the Danish electricity and heat demand are produced in CHP and more than 15% of the electricity demand is produced by Wind Turbines. Both technologies are essential for the implementation of Danish Climate Change Response objectives, and both technologies are intended for further expansion in the coming decade. Meanwhile, the integration of CHP and wind power are subject to fluctuations in electricity production. Wind turbines depend on the wind, and CHP depends on the heat demand. This article discusses and analyses two different national strategies for solving this problem. One strategy, which is the current official government policy known as the export strategy, proports to take advantage of the Nordic and European markets for selling and buying electricity. In this case, surplus electricity from wind power and CHP simply will be sold to neighbouring countries. Another strategy, the self-supply strategy, argues to run the CHP-units to meet both demand and the fluctuations in the wind scheduling. In this case, investments in heat-storages are necessary and heat pumps have to be added to the CHP units. Based on official Danish Energy Policy and Energy Plans, this article quantifies the problem for the year 2015 in terms of the amount of surplus electricity, investments in heat pumps, etc. needed to solve the problem are calculated. Based on these results between the two different strategies, the conclusion is that the self-supply strategy is recommended over the official export strategy.

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Nomenclature

Annual demands (TWh/year)

Q_{DH}	District heating demand
Q_S	Production from solar collectors for district heating
Q	Heat production from CHP, Heats Pumps and Boilers
W_D	Electricity demand
W_E	Electricity export
W_I	Electricity import
W_W	Wind power production
W	Electricity production from CHP, Heat Pumps and Power stations
F_{CHP}	CHP fuel demand
F_B	Boiler fuel demand
F_P	Power stations fuel demand

Average productions in period i (MW – MJ/s)

Qi	Heat production from CHP, Heat Pumps and Boilers
Wi	Electricity production from CHP, Heat Pumps and Power stations
q_{CHP}	CHP heat production
q_{HP}	Heat Pump heat production
q_B	Boiler heat production
w_{CHP}	CHP electricity production
w_{HP}	Heat Pump electricity demand
w_P	Power Plant electricity production

Efficiencies

μ_{CHP}	CHP heat efficiency
ε_{CHP}	CHP electricity efficiency
μ_B	Boiler heat efficiency
ε_P	Power Plant electricity efficiency
COP_{HP}	Heat Pump coefficient of performance

Capacities (MW – MJ/s)

C_{HP}	Heat Pump capacity
C_{CHP}	CHP Capacity (MW-electric)
C_P	Power Plants (MW-electric)
C_B	Boilers (MJ/s heat)
$C_{W\text{-}PEAK}$	Electric peak capacity
$C_{W\text{-}P+R}$	Electric peak and reserve capacity
$C_{Q\text{-}PEAK}$	Heat peak capacity
$C_{Q\text{-}P+R}$	Heat peak and reserve capacity

1. Introduction

Danish plans for the implementation of CO_2-reduction targets according to the Coyote accords and EU guidelines are characterised by replacing energy systems based on large power plants with far more decentralised systems based on energy efficiency at the community level of consumption with renewable energy systems are adapted to local conditions. Such a policy shift requires national strategies and programs for the management of fluctuations in wind power and CHP.

Security of supply and climate change response are major policy objectives for the energy strategies of Denmark and other European countries. During the past 20 years these objectives have been expressed through a number of energy plans adopted by the Danish Parliament. During the period from 1972 to 1990, the major objective was to become less dependent on oil imports. Since 1990, Danish energy policy's main objective, expressed by the national energy plan and further supported by the Kyoto accords, has been to reduce the CO_2-emissions by 20% before the year 2005 [1]. Since then, the objective has been confirmed by the energy plans [2-3]. In March 1997, Denmark participated in the European Council decision to reduce the 1990 CO_2-emission rates by 10% before 2010. According to this decision, Denmark has to reduce its CO_2-emissions by 25% of 1990 emissions [4,5].

In the 1970s and 1980s, the strategic objective for energy security of supply was met by: 1) energy savings, 2) increasing oil production and 3) a replacement of oil with other fuels, mainly coal and natural gas. Houses were insulated and central heating systems were converted from oil to natural gas or district heating based on coal-fired CHP plants. Power plants replaced oil with imported coal and over a period of five years the Danish electricity production changed from 90% use of oil to 95% use of coal.

Over the same period Denmark itself began to extract oil and natural gas from the North Sea. By turn of the century, Denmark has a net export of oil and natural gas [6].

Danish energy policy has also succeeded in meeting the objective of climate change response. First, insulation of houses and an extensive expansion in the use of CHP has lead to decreased fuel consumption for domestic heating, which was achieved during a period of 20 years of economic growth in which the number of houses has increased. Second, different types of renewable energy have been introduced and strongly supported by the government [19]. Wind power as an industry is a good example, in which Danish wind power now is producing approximately 15% of the Danish electricity supply [7].

However, Danish energy policy has also failed. For example, the expansion of decentralised CHP was delayed for several years because the potential was considered too small to motivate development. Also, large investments were made in thermal insulation during the 1970s and 1980s, while none were made in electricity savings. This resulted in increased fuel consumption for electricity production, while the fuel consumption for domestic heating decreased.

Parliament's climate change response in 1990 described various types of strategies to reach the objective. According to the Government's energy plan from 1990 [1], the technology of coal-fired power generation has to be replaced by new technological solutions, such as energy conservation, decentralised CHP and renewable energy. Since 1990, all strategies in Parliament's energy plans have been based on these principles of technology change, so Denmark must change its energy technology strategies radically [8,9].

As opposed to the older - conventional technologies such as coal-fired power plants, the new technologies are widely distributed throughout the areas of clean consumption and efficiency. Therefore, the implementation is characterised by decentralisation of the electricity production. Removing dependency of regions and communities from the grid while integrating them into a national plan and protecting environmental laws accomplishes many things. The potential for implementing such a policy can be seen in a number of models and actual local or regional application of distributed energy systems [21].

- Clean electricity consumption is planned to be stabilised by (a) energy conservation and efficiency which is (b) the replacement of electric heating by district heating or by individual boilers in combination with solar heating [10].
- Some centralised coal-fired power plants are being supplemented or replaced by a number of local CHP units fuelled with natural gas or local biomass fuels [11].
- Wind power will be expanded onshore to a total of 1500 MW.
- Wind power offshore is planned to expand substantially (Some demonstration and experimental offshore plants has already been built). Two 150 MW offshore wind farms are planned to be in operation by the end of 2003 and the potential is estimated to be several thousand MW.
- Various other technologies that exploit renewable energy sources, such as solar cells and wave power plants, are being introduced.

This radical change in technological strategies is a challenge to the planning and design of the future energy system.

The implementation of sustainable energy solutions has placed Denmark in an international leading role with regard to insulation of houses, building of wind turbines and CHP. Wind power now meets nearly 15% of electricity demand, whereas the share of CHP is 50%. And both CHP and wind power are still being expanded. Together, this means that Denmark has become an international leader in terms of facing possible power regulation problems. For example, a number of strategies well established in Denmark are being implemented in California [20]. For example, California has targeted 25% of its energy generation to be renewable by the year 2020. This is a substantial increase over the current level of 10% including all wind by 2001. This paper discusses whether to integrate heat pumps and storage devices into the local energy systems, or to export surplus electricity production in order to tackle the problems of regulation. The same policy debate faces California, other states, and nations.

2. The Official Danish Strategy: import/export-dependency

The present official Danish energy policy is guided by the Government Action Plan for Energy, known as Energy 21 [3], which specifies sub-objectives and programs for energy conservation and renewable energy in 2005. These are not presented as independent targets but as consequences of the steps necessary in order to reach the 20% CO_2-reduction target in 2005. The consequences for the year 2005 are that energy conservation will improve by approximately 20% from 1994, and that renewable energy generation will have expanded to about 12-14% of estimated energy consumption. In order for CO_2-emissions to be halved before 2030 the energy conservation must be improved by approximately 55% over 1994 standards and renewable energy generation must be expanded to about 35% of estimated energy consumption [3].

The Danish Energy Agency has made various calculations on the necessary technological changes in the energy system in order to implement Energy 21. Such calculations have been based on the expansion of both CHP and renewable energy with an emphasis on wind power. And, to some extent, the calculations have quantified the problem of making fluctuations in power from CHP and wind meet the fluctuations in demand. All of the calculations have been based on the principle that import/export of electricity in liberalised Nordic and European markets would solve this regulation problem simply by selling surplus production.

The Danish Energy Agency calculations have been adjusted over time according to adjustments in the implementation strategy. Table 1 shows the main figures of the latest calculation [12]. From table 1, the official strategy can be seen as based upon substantial expansion of exports, which are necessary in order to solve the problem of fluctuations in power production from CHP and wind. According to preliminary estimations the surplus production in year 2030, the surplus becomes as high as 5500 MW in a windy winter week. Thus, the implementation of this strategy results in an estimated need of expanding the high voltages exchange capacity by approximately 2000 MW [12].

3. An Alternative Strategy: self-supply

The implementation of Energy 21 with the planned regulation strategy leads to a situation in which Denmark will be forced to export electricity during certain - non-predictable - periods. This strategy is fallicious particularly on three important points:

1. By being forced to produce and sell during certain periods, Denmark will be placed at an economic disadvantage when prices are negotiated.
2. The Danish export implementation strategy prevents neighbouring countries from implementing similar strategies. Clearly, the Danish implementation of climate

change response is part of the international actions on a global scale. However, for example, Germany would benefit from implementing much more CHP [13]. In such a case, Denmark, Germany and other countries would need to export wind and CHP surplus production simultaneously. The market would be clutted causing economic chaos in all markets.

3. Since the only logical exchange of power with this strategy is via high voltages transmission lines in Denmark, it will result in substantial expansion. Even the present plans of minor transmission expansion are facing local resistance because of the probable damage to the landscape; The additional costs, management and control operations futher complicate the overall system as well as increase costs and mitigate energy security.

Instead, below argues for an alternative strategy of "self-sufficiency". The aim herein is to implement the official Danish energy policy as put forward in Energy 21, but in a way in which Denmark is not forced to export or import energy. The self-sufficiency strategy does not prevent Denmark from selling and buying electricity on Nordic or European markets. But it provides Denmark with the opportunities of choosing if and when to sell and buy. Denmark therefore would have control over the economics of its energy sector. Such a strategy is presented below and compared with the export-strategy on the following assumptions:

- Export figures have decreased to zero.
- Further investments in heat pumps are added in order to convert surplus electricity to district heating.

- The need for CHP-unit capacities increases by 20% compared to the export strategy in order to make CHP-production vary according to fluctuations in wind power production as well as in electricity and heat demands.

The implementation of the self-sufficiency strategy requires public and private sector investment in heat-storages as Denmark has done in the past [19]. However, such investments are already included in the export strategy. Moreover, such a self-sufficiency strategy provides the possibility of decreasing the share of peak load boilers in district heating. The changes are illustrated in Table 2. Finally, the self-supply strategy can be implemented without further expansion of the high voltage transmission system [14].

It should be emphasised that this strategy is not the only possibility for managing the fluctuations. Several other programs and technological means could be added to support the self-sufficiency strategy. For instance load management could make it possible for the demand partly to follow the fluctuations of the wind power production. Recent studies indicate that between 8-10% of the Danish electricity demand might become flexible, if certain public regulation measures were introduced [15, 16]. Nevertheless load management will not be able, solely, to solve the problem, but should be considered an important additional tactic.

4. Calculation Model

The two alternatives have been compared on a simple input/output-model described in the following. The model calculates annual energy balances on the basis of 26 two week periods. Meanwhile wind power fluctuations are much more rapid, being hourly at local level and 12 hours at international market levels [17]. Therefore the model calculates needed peak and reserve power and heat capacities on the basis of typical relations between annual demands and peak-loads and need for reserve. Typically the electricity peak load is 166% of the average load and reserve capacity is minimum additional 20% of peak load.

The model needs three sets of input. The first is the annual district heating consumption and the annual consumption and import/export of electricity together with the annual production by wind turbines. The second is operation efficiencies of CHP-units, power stations, boilers and heat pumps. And the third is the capacity of heat pumps.

First the necessary annual electricity production from CHP-units and power stations are calculated by subtracting wind power and import/export from the electricity consumption.

Annual demands for CHP + Heat Pumps + Boilers + Power Plants (TWh/year):

$Q = Q_{DH} - Q_S$

$W = W_D + W_E - W_I - W_W$

Then, the model calculates Q and W in periods of two weeks. The annual consumption is distributed into 26 periods of two weeks based on statistics of a Danish average distribution.

Statistics for typical distribution of annual demands on 26 two-week periods:

$Q = \Sigma\, q_i \quad (i = 1 \text{ to } i = 26)$

$W = \Sigma\, w_i \quad (i = 1 \text{ to } i = 26)$

In each period the model calculates the resulting energy balance in four steps:

1. The potential CHP district heating production is calculated in a case in which all the electricity is produced on CHP units. The number is reduced BECAUSE it is higher than the district heating demand of that period
2. Then, based on the heat pump input capacity, the potential heat pump district heating production is calculated. The additional electricity demand from the heat pumps should be produced from either CHP-units or power stations. Thus, the calculation includes the additional possibilities for CHP heat production that supplies the additional electricity for heat pumps. Again the number is reduced SINCE it is higher than the district heating demand of that period.
3. The heat production on boilers is found as the difference between the demand and the production by CHP-units and heat pumps.
4. The electricity production by power stations is found as the difference between demand and production by CHP-units IS subtracted FROM the demand for heat pumps.

Energy balance - calculations for each 26 two-week periods (TWh/period):

$q_{CHP\text{-}A} = w_i * \mu_{CHP}/\varepsilon_{CHP}$ [If $q_{CHP\text{-}A} > q_i$ then $q_{CHP\text{-}A} = q_i$]

$q_{CHP+HP} = C_{HP} * (COP_{HP} + \varepsilon_{CHP}/\mu_{CHP}) * (8760 / 26)/1,000,000$

[If $q_{CHP\text{-}A} + q_{CHP+HP} > q_i$ then $q_{CHP+HP} = q_i - q_{CHP\text{-}A}$]

CHP heat production: $q_{CHP} = q_{CHP\text{-}A} + q_{CHP+HP} * (\varepsilon_{CHP}/\mu_{CHP})/(COP_{HP} + \varepsilon_{CHP}/\mu_{CHP})$

Heat Pump heat production: $q_{HP} = q_{CHP+HP} * \Phi_{HP} /(\Phi_{HP} + \Phi_{CHP}/\Psi_{CHP})$

Boiler heat production: $q_B = q_i – q_{CHP} - q_{HP}$

CHP electricity production: $w_{CHP} = q_{CHP} * \Phi_{CHP}/\Psi_{CHP}$

Heat Pump electricity demand: $w_{HP} = q_{HP} / \Phi_{HP}$

Power Plant electricity production: $w_P = w_i - w_{CHP} + w_{HP}$

The (NAME) model provides two sets of output. The first is the required capacities of CHP-units, power stations, and peak boilers. And the second is the fuel consumption distributed on the different types of units. Fuel consumption for each type of production unit (CHP-units, boilers and power stations) is founded on the production and the input efficiencies.

Annual fuel demands (TWh/year):

CHP fuel demand: $F_{CHP} = \Sigma\, q_{CHP} / \mu_{CHP}$

Boiler fuel demand: $F_B = \Sigma\, q_B / \mu_B$

Power Plan fuel demand: $F_P = \Sigma\, w_P / \varepsilon_P$

Based on the energy-balance the model calculates the capacities as follows:

- The CHP-units in the official Danish import/export strategy is found so that they can meet the winter heat demand. In the alternative strategy the CHP capacities are raised by 20% in order to make it possible to regulate electricity production according to the wind power.
- As derived from the Danish statistics the maximum electricity consumption is seen as 166% of the average consumption. The heat pump capacity and a 20% reserve capacity are added to this number in order to find the total capacity demand. The necessary peak load power capacity is then found as the difference between the total demand and the CHP capacities.

- The required heat production capacities are calculated by adding a 100% reserve to the maximum heat demand. The necessary boiler capacity is found by subtracting heat pumps and CHP capacities from this number.

Peak-load and reserve capacity needs (MW or MJ/s):

$C_{W\text{-}PEAK} = 1{,}66*(W_D*1{,}000{,}000/8760) + C_{HP}$

$C_{W\text{-}P+R} = 1{,}2 * C_{W\text{-}PEAK}$

$C_{Q\text{-}PEAK} = (q_{MAX}*1{,}000{,}000)/(8760/26)$

$C_{Q\text{-}P+R} = 2 * C_{Q\text{-}PEAK}$

Necessary capacities (MW or MJ/s):

CHP (MW-electric): $C_{CHP} = q_{CHP\text{-}MAX} * (1{,}000{,}000/(14*24)) * (\varepsilon_{CHP}/\mu_{CHP})$

Power Plants (MW-electric): $C_P = C_{W\text{-}P+R} - C_{CHP}$

Boilers (MJ/s heat): $C_B = C_{Q\text{-}P+R} - (C_{CHP}/\varepsilon_{CHP})*\mu_{CHP} - C_{HP}*COP_{HP}$

When using the described model, one can change the heat pump capacity input in order to find a suitable balance between investments in heat pumps and fuel savings. The model calculates the peak-load boiler share as an indicator for finding such balance. Normally CHP-units in Denmark have an optimal size, when the peak-load boiler share is about 5 to 10%.

5. Comparison

Based on the input described previously in Tables 1 and 2 and the efficiencies in table 3, the two different strategies have been compared using the calculation model for the year 2015. The results are shown in Table 4. As illustrated by the results in Table 4 the implementation of the self-supply strategy instead of the official export-dependency strategy entails additional investments in CHP-units, heat pumps and power stations. Such additional capacities will save some of the need for boiler-capacity. Yet this does not influence the total costs very much since boilers are very inexpensive. In Table 4 the implementation of the self-supply strategy is illustrated by zero export and subsequently much lower fuel consumption. Of course it is possible to export also in the self-supply strategy, but in this case the export is not forced and the electricity can be produced in periods with high prices.

The comparison can be used to find the total production cost of electricity that Denmark is forced to export in the official export-dependency strategy. Consider such a calculation in Table 5. The construction costs are based on typical Danish investments, and the operation and maintenance costs are based on running costs of typical existing production units. The fuel costs are calculated on the assumption that all additional fuel in year 2015 will be natural gas and the prices are set to 1.2 DKK/m3 equal to 0.11 DKK/kWh or approximately 0.016 Euro/kWh.

In Table 5 the total net construction costs of implementing the self-supply strategy is calculated and found to be 4,696 million DKK. With an interest of 5% and a period of 20 years this amount equals annual costs of 377 million DKK. When saved fuel costs and operation and maintenance costs are subtracted the total annual production costs of exporting 5.88 TWh are then 1,153 million DKK. The calculation in Table 5 does not include the saved construction costs of expanding the high voltage exchange capacity mentioned earlier. Furthermore it should be emphasised that the calculation is rather sensitive to the fuel costs.

The result is that with a natural gas price of 1.2 DKK/m3 (equal to 0.016 Euro/kWh), the production price of the forced electricity export in the official Danish energy plans is as high as 0,20 DKK/kWh (equal to 0.029 Euro/kWh). This price could be compared with the spot market prices on the Nordic markets represented by NORDPOOL, where the prices fluctuate between 0.10 and 0.15 DKK/kWh. Even though the price has been low in the first years and might raise in the future, such a comparison indicates that the implementation of the official Danish export strategy does not seem to be a good idea from a strictly business point of view.

6. Conclusions

Both CHP and Wind Power are important elements of Danish Energy Policy. Meanwhile both technologies are subject to fluctuations in the electricity production. Wind turbines depend on the wind, and CHP depend on the heat demand. Similar considerations face almost all countries as they confront creating clean energy generation to meet national and international policies to lower CO_2 emissions.

This article has compared two different national strategies in Denmark for solving this problem. The current official Danish export strategy purports to take advantage of Nordic and European markets for selling and buying electricity. Another strategy, the self-supply strategy, is to run the CHP-units in order to meet both demand and the fluctuations in the wind. In this article additional investments of the self-supply strategy have been estimated to annual costs of 377 million DKK. This amount constitutes the costs of getting a production system that allows to decide *whether or not* (and if that were the case) then *when* to produce electricity for export, instead of being forced to sell in certain periods depending of fluctuations in the wind and heat demand.

According to the Danish Energy Agency, the export approach is the official Danish strategy. By comparing the two different strategies a production price of the "forced electricity for export" in such a strategy is found to primarily depend on the fuel-price. For a natural gas price of 1.2 DKK/m^3 the production price was estimated to BE 0.20 DKK/kWh. This price WAS compared with the spot market prices on the Nordic markets, represented by NORDPOOL, where the prices fluctuate between 0.10 and 0.15 DKK/kWh. Such a comparison strongly indicates that the implementation of the official strategy does not seem to be a good idea from a strict business point of view with present spot-market prices. Meanwhile these spot-market prices can be seen as the result of abnormally high precipitation in Norway and Sweden, and possible future spot market prices are hard to predict. Furthermore market imperfections should be taken into account [18].

Denmark does not necessarily have to choose now whether we will export electricity in year 2015 or 2030. But we have to choose whether the energy-production system should be constructed according to the one or the other strategy. In the export strategy, Denmark will be forced to produce surplus-electricity that will likely be sold below the production prices. In the self-supply strategy, Denmark will be able to choose whether to export or not, and if so when to export.

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7. References

[1] Danish Ministry of Energy. Energy 2000: A Plan of Action for a Sustainable Development. Copenhagen: Danish Ministry of Energy, 1990.

[2] Danish Ministry of Energy. Energy 2000 - Follow up; Responsible and Forward Looking Energy Policy. Copenhagen: Danish Ministry of Energy, 1993.

[3] Danish Ministry of Environment and Energy. Energy 21. The Danish Governments Action Plan for Energy. Copenhagen: Danish Ministry of Environment and Energy, 1996.

[4] European Council. Council meeting – Environment. Brussels: 3 March 1997.

[5] Danish Environmental Protection Agency. Climate Protection in Denmark, National Report of the Danish Government in Accordance with Article 12 of the United Nations Convention on Climate Change. Copenhagen: Danish Environmental Protection Agency, 1994.

[6] Lund H. Choice Awareness. The Development of Technological and Institutional Choice in the Public Debate of Danish Energy Planning. Journal of Environmental Policy & Planning 2000;2:249-259.

[7] Christensen P, Lund H. Conflicting Views of Sustainability: The case of Wind Power and Nature Protection in Denmark. European Environment 1998;8:1-6

[8] Hvelplund F et al. Demokrati og Forandring, Energihandlingsplan 1996 (Democracy and Change, Energy Action Plan 1996). Denmark: Aalborg University Press October 1995.

[9] Lund H, Hvelplund F. Does Environmental impact assessment really support technological change? Analysing alternatives to coal-fired power stations in Denmark, Environmental Impact Assessment Review 1997;17(5):357-370.

[10] Lund H. Implementation of energy-conservation policies: the case of electric heating conversion in Denmark. Applied Energy 1999;64:117-127

[11] Mæng H, Lund H, Hvelplund F. Biogas plants in Denmark: technological and economic developments. Applied Energy 1999;64:195-206

[12] Danish Energy Agency. Detaljeret beskrivelse af alternativ B. Danish Ministry of Environment and Energy June 1998.

[13] Hvelplund F, Lund H. Rebuilding without restructuring the energy system in east Germany. Energy Policy 1998;26:535-546

[14] Lund H, Østergaard P. Electric grid and heat planning scenarios with centralised and distributed sources of conventional, CHP and wind generation. Energy 2000;25:299-312

[15] Togeby M, Pedersen T E, Munksgaard J, Larsen A, Petersen C J, Ramskov J. Fleksibilitet i elforbrugt. Copenhagen: Elkraft-system, June 2001.

[16] Almeida M A, Schaeffer R, La Rovere E L. The Potential for electricity conservation and peak load reduction in the residential sector of Brazil. Energy 2001;26:413-429

[17] Skytte K. The regulating power market on the Nordic power exchange Nord Pool: an econometric analysis. Energy Economics 1999;21:295-308

[18] Skytte K. Market imperfections on the power markets in northern Europe: a survey paper. Energy Policy 1999;27:25-32

[19] Clark W W, Jensen J D. The Role of Government in Privatization: An Economic Model for Denmark. International Journal of Technology Management 2000 (Woody add here vol and pages….XXXX)

[20] State of California. Energy Infrastructure Plan (Section). 21st century Infrastructure Commission. State of California, 2001.

[21] Isherwood W, Smith J R, Aceves S, Berry G, Clark W W, Johnson R, Das D, Goering D, Seifert R. Remote Power Systems with Advanced Storage Technologies for Alaskan Villages. University of Calif., Lawrence Livermore National Laboratory. UCRL-ID-129289: January 1998. London: Elsevier, Energy Policy, 2000.

Table 1
Official Danish Energy Plan "Energy 21" according to the Danish Energy Agency, 1998 [11]

TWh/year	Year 2005	Year 2015	Year 2030
District heating production	34.65	35.10	34.23
Solar collectors	- 0.03	- 0.03	- 0.03
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CHP (incl. Peak load boilers and heat pumps)	34.62	35.07	34.20
Electricity demand	33.80	34.04	31.21
Wind power, etc.	- 5.20	- 9.23	- 17.96
Export	4.27	5.88	13.98
Import	-	- 1.19	- 2.19
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Rest (CHP + heat pump)	32.87	29.50	25.04

Table 2
Alternative "Energy 21" implementation

TWh/year	Year 2005	Year 2015	Year 2030
District heating production	34.65	35.10	34.23
Solar collectors	- 0.03	- 0.03	- 0.03
---------------	-------------	------------	------------
CHP (incl. Peak load boilers and heat pumps)	34.62	35.07	34.20
Electricity demand	33.80	34.04	31.21
Wind power, etc.	- 5.20	- 9.23	- 17.96
Export	4.27	0.00	0.00
Import	-	- 1.19	- 2.19
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Rest (CHP + heat pump)	32.87	23.62	11.06

Table 3
Efficiency input data

CHP electricity efficiency	40%
CHP heat efficiency	50%
Power Plant electricity efficiency	45%
Boiler heat efficiency	90%
Heat Pump coefficient of performance	3

Table 4
Results of comparing the two different regulation-strategies in year 2015

	Export-dependency Regulation strategy	Self-supply Regulation strategy	Additional investments if self-supply is implemented
Capacities:			
CHP-units (MW-electric)	3877 MW	4062 MW	185 MW
Power Plants (MW-electric)	3957 MW	4279 MW	322 MW
Heat Pumps (MW-electric)	78 MW	500 MW	422 MW
Boilers (MJ/s heat)	9159 MJ/s	7662 MJ/s	- 1497 MJ/s
Electricity production			
Export	5.88 TWh/year	0.00 TWh/year	- 5.88 TWh/year
Fuel demands (TWh/year):			
CHP-units	60.06 TWh/year	54.25 TWh/year	- 5.81 TWh/year
Power Plants	12.85 TWh/year	8.62 TWh/year	- 4.23 TWh/year
Boilers	4.58 TWh/year	2.31 TWh/year	- 2.27 TWh/year
Sum	77.49 TWh/year	65.17 TWh/year	- 12.31 TWh/year

Table 5
Calculation of production costs pr. kWh of electricity export in the export-dependency strategy

	Difference	Cost pr. unit Million DKK/unit	Total Costs Million DKK	Annual Costs Million DKK/Year
Construction:				
CHP-units	185 MW	6	1,111	
Power Stations	322 MW	4	1,285	
Heat Pumps	422 MW	9	3,798	
Boilers	- 1,497 MJ/s	1	-1,497	
Sum			4,696	377
Operation and M.				
CHP-units	-2.32 TWh elec.	60	-139	
Power Stations	-1.90 TWh elec.	60	-114	
Heat-Pumps	-4.95 TWh th.	20	99	
Boilers	-2.05 TWh th.	10	-20	
Sum			- 175	-175
Fuel consumption				
CHP-units	-5.81 TWh	110	-639	
Power Stations	-4.23 TWh	110	-466	
Boilers	-2.27 TWh	110	-250	
Sum			-1,355	-1,355
Total annual additional costs of implementing the self-supply strategy				- 1,153 million DKK
Total annual additional export of electricity				-5.88 TWh
Marginal unit production costs of electricity export				0.20 DKK/kWh