Introduction of Renewable Energy Systems in Remote Communities in the Nordic Region
–
A Case Study of Nólsoy, the Faroe Islands

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Preface

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Abstract

This thesis investigates the setup of a stand-alone energy system where the excess wind power is diverted to and consumed in distributed domestic hot water tanks. The purpose of this setup is to utilize wind power that would otherwise go to waste, and using it for heating tap water and in space heating, substituting fuel oil combustion.

The first part of the thesis is devoted to local energy planning. Yearly consumption data for electricity and oil are collected from questionnaires, statistics and calculations. Normalized load profiles on a yearly and 24 hours basis are generated using temperature profiles and load plots.

The second part involves building and configuring a TRNSYS simulation model for the energy system of Nólsoy. Energy consumption data, load profiles and a local wind series are loaded into the simulation model. Three different setups are investigated:

Scenario I is a classic wind-diesel configuration, and will be used as a reference system. With a 300 kW windmill the diesel consumption is halved compared to a pure diesel generator setup. However, more than 50% of the generated wind power has to be dumped.

The main idea behind scenario II is to utilize the excess wind power that would otherwise be dumped in distributed domestic hot water tanks, one in each household (102 in total). A number of simulations are run, now with a windmill size of 800 kW, in order to configure the system and the tank parameters. A relatively large storage tank of 1000 litres and a moderate heating element of 1000 W give the best energy yield; covering 75% of the tap water load and reducing the oil consumption with over 31000 litres, 304 litres per household.

In Scenario III the tap water load is replaced with a space heating load that is more than 7 times bigger. In contrary to scenario II, a reduction of the tank size and an increasing of the rated power yield the best results. This is a result of the large power demand, meaning that all added power will be continuously consumed by the load, meaning a large thermal storage is not needed. With a 50 litre tank and a 1500 W heating element, the excess wind power covers 25% of the heating load, reducing the fuel oil consumption by nearly 78000 litres, 765 litres per household.

An economical analysis shows that scenario III is the most profitable, giving an energy price of 0.03 €/kWh compared to scenario II's 0.075 €/kWh. The reason is that both scenarios require mostly the same hardware, but scenario III has greater energy utilization. Both scenarios' energy cost is competitive to the current fuel oil price of approximately 0.079 €/kWh.

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Acronyms

COE	Cost of Energy
DEGS	Diesel Engine Generator System
DHT	Domestic Hot water Tank
ETS	Electric Thermal Storage
O&M	Operation and Maintenance
SAPS	Stand-Alone Power System
TWS	Thermal Water Storage
WECS	Wind Energy Conversion Systems

1 Introduction

1.1 Background

The West Nordic Islands, which includes Greenland, Iceland and the Faroe Islands, are covering a great geographical area with numerous towns and rural districts that are not connected to the central electricity grid. These communities have their own electricity and heat production with a local transmission network. In addition there are several sites that have a weak and vulnerable connection to the central grid, often with a local electricity generating unit as a supplement and backup.

The electricity and heat generation in these settlements are to a large extent based on fossil fuel like fuel oil and diesel. A great disadvantage with these kinds of energy systems is the society's dependency on fuel import, which is both bothersome and costly due to the great distances. Coupled with a steadily rising fuel price, the energy situation is becoming a growing concern and economic load on the local communities.

Environmental issues are another important motivator to reduce the consumption of fossil fuels, which generates emission of CO_2 and other greenhouse gasses when combusted. There will also be a risk of local oil spills when such energy carriers are used.

An increasing political focus on reliability of energy supply and environmental aspects, as well as a growing activity on energy research and eco-tourism, has given an intensive to speed up the work on renewable energy sources in these areas. A first step would be to utilize local renewable energy sources, such as wind, sun, hydro- and wave power in combination with traditional concepts like diesel and fuel oil. Future concepts with hydrogen as an energy carrier might also be an interesting alternative.

Within this setting the Nordic Council of Ministers decided to fund research on the off-grid energy supply in the West Nordic region, and the "Vestnorden Project" was launched at the turn of the year 2003/2004. The project work was performed by ”Nordisk Energiforskning”, ”Institutt for Energiforskning”, ”ECON Analyse”, ”NIRAS A/S”, in addition to various local participants on Iceland, Greenland and the Faroe Islands.

The project is separated into two parts. The first part looked at the energy situation for a selection of localizations in the West Nordic region; some of which were investigated closer. Local and national parties such as public officials and energy companies were included in the process to ensure a local connection.

The first part of the project was finished in 2005, and one of the localizations chosen for further study was Nólsoy, a small island in the Faroe Islands.

Part two of this project is currently in progress, and the main focus will be to perform a technical and economical analysis of different system configurations based on renewable energy.

This thesis is written with the guidance of members of the Vestnorden Project group and is also based on results from part one of the project, but is not officially affiliated.

1.2 The Nólsoy case study

Renewable energy systems have a well-established history of supplying electric power in remote, off grid areas. Such off-grid locations play an important role in technology development as the high energy cost means that a hybrid system can become competitive much earlier than in an urban environment. Alaska has more than 200 rural villages that have no link to the central power grid, and are in most cases relying on electricity generated in diesel-driven generators (Cotrell & Pratt, 2003). Because of the remoteness of these locations the fuel and O&M prices are high, resulting in electric generation costs that average nearly 0.30 €/kWh and can be as high as 0.80 €/kWh (Drouilhet & Shirazi, 2002).

Wind-diesel systems have been utilized with success in many stand-alone energy systems for the last decades. A fundamental problem for such systems is the renewable energy penetration rate, since there will frequently be a mismatch between the fluctuating wind energy generation and the load. Adding an energy storage element will in most cases improve system performance, but large-scale electric energy storage is generally considered to be uneconomical for such applications (Johnson el al., 2002). In communities with a large share of fossil fuel consumption and a large heating demand, like the west-Nordic region, it might be more economical to convert the excess power to thermal energy that can be stored relatively cheap. This is not a new idea, and several concepts have been proposed and implemented (Hunter & Elliot, 1994; Drouilhet, 1999; Johnson et al., 2002). Most of these concepts use one or more big dump loads for the thermal system. A disadvantage with this system is that depending on the location, only parts of the heating demand can be covered. It is also limited how well one dump load can be adjusted to fit the available power.

In order to investigate the performance and concept of stand-alone systems with a thermal dump load, the purpose of this thesis is to design and model a renewable energy system with numerous distributed energy storage units, DHTs, for the island of Nólsoy.

The first part of the thesis is devoted to an energy analysis of the local community, where energy consumption and load profile is generated from consumption statistics, questionnaires and climatic data.

The second part will address the development and modelling of different scenarios with a thermal dump load. These scenarios will be simulated in a transient simulation program and discussed in regards to system configuration and -performance.

2 System studies

2.1 Energy system

This chapter is a rewrite of chapter 2 of "Decentralized energy supply based on renewable energy sources", 2005, by the writer.

The energy system on the Faroe Islands, like many other typical island communities, relies heavily upon fossil fuels to cover the energy demand, because the lack of alternative energy sources. The main fuel consumers are the fishing fleet and the stationary diesel and oil aggregates used in electricity production. The Faroe Islands differ however; since a substantial part of the electricity production is based on renewable sources, mainly hydro power.

SEV, the Faroe Islands publicly owned energy company, runs the electricity grid and has historically been the sole producer of electricity fed intro the grid. However, the Faroe Islands Competition Authorities have ruled that the electrical supply network is affected by the competition laws, thus possibly allowing third party access to the grid. This is a step on the way to liberating the energy market, and can have great impact on SEV, as well as for the Faroe island energy market.

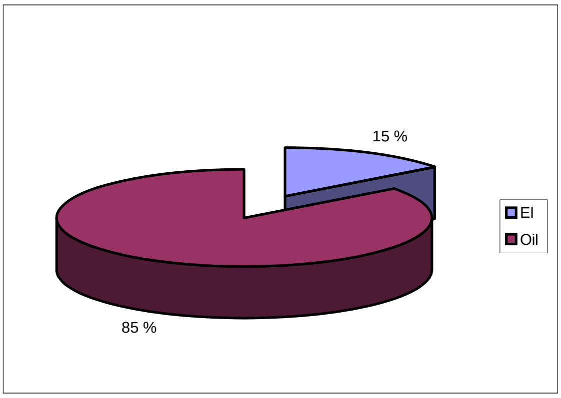


Figure 1 - Energy cons. households, Faroe Islands

Figure 1 and Figure 2 illustrate the Faroe Islands' dependency of fossil fuels, as well as Norway's dependency on electricity. 85% percent of the households' energy consumption is fuel oil, used for space heating and tap water. With the oil price more than the double of what it was just a decade ago (SSB, 2006), the energy expense has become a big concern and a debated topic for the Faroese. Because 60% of the country's electricity is generated from oil fuelled generators, this is affecting the electricity cost as well.

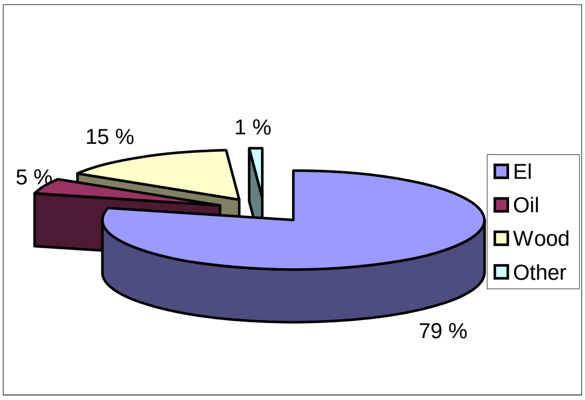


Figure 2 - Energy cons. households, Norway

Figure 3 shows an overview of the Faroe Islands energy consumption for 2001. More than a third of the energy consumption is related to fisheries, which also contributes to 27% of the disbursed salary for 2001. Fish and fish products is also by far the largest export article, and amount to 98% of the country's total export. Fluctuations in the fisheries can have a major impact on the Faroese economy, last seen in the 1990s when a crisis in the fish industry caused a major emigration and a serious economic decline. Since then the fish industry and economy has recovered and is still growing, resulting in a 30% increase in energy consumption since 1994.

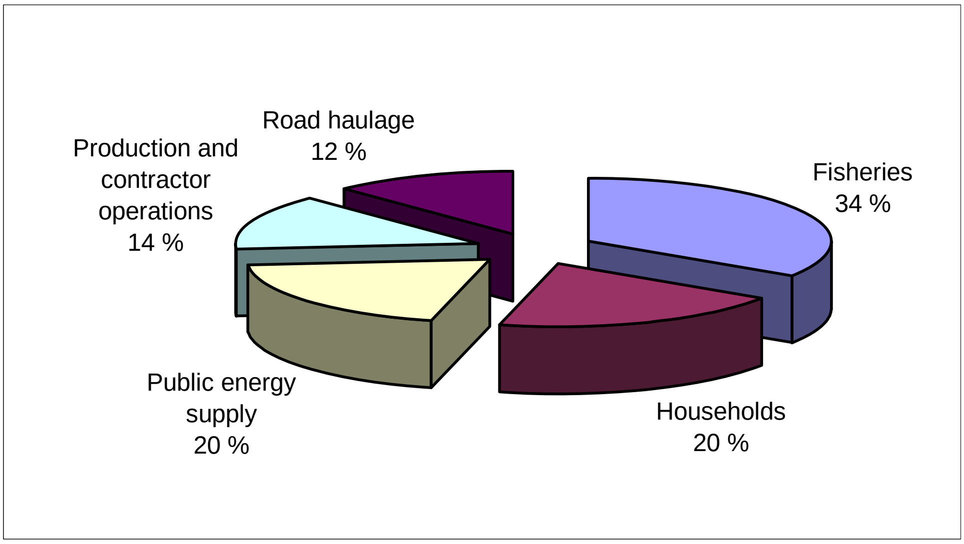


Figure 3 - Energy consumption per sector, the Faroe Islands (2001)

	1999	**2000**	**2001**	**2002**	Share
Hydro	75.955	96.500	85.687	94.387	38%
Thermal	154.760	143.230	160.286	147.026	59%
Wind	504	553	2.993	7.509	3%
Total	231.219	240.283	248.966	248.922	100%

Figure 4 – Electricity production, Faroe Islands [MWh]

Table 4 shows the produced electrical energy in the period 2001-2004 by energy source (Hagstova Føroya, 2005). The figures show a relatively high share of hydropower, as well as a small but rising wind power production. Having a large share of hydropower is a great asset for the energy system because it can be quickly regulated to fit the variable power output of wind mills, without the losses of efficiency a thermal plant with the same operation would experience. Thermal plants are still the dominant producer of electricity, covering nearly 60 percent of the demand. Most plants run on light or heavy oil, and have a power output between 2 and 14 MW. Because such small power stations lack the efficiency and treatment plants of bigger units, they are rather pollutive and contribute to the reason why the Faroe Islands have one of the highest emission rates of CO_2 per inhabitant in the world (UNSD, 2005). Wind power is gaining grounds, but the installed effect is still small. The total amount of electricity produced by wind power in 2005 was 7.5 GWh, approximately 3% of the total production. Still, this is the double of 2003 production and a sign that wind power is an area of interest in the Faroe Islands. Wind conditions are generally very good, but there are several disadvantages that could thwart the plans for an increase in the wind power production. The harsh climate with strong wind gusts puts special requirements on the windmills, leading to higher installation costs than for a normal site. Another major disadvantage for wind power is the weak power grid, limiting the maximum installed effect. When the current projects are finished, the total wind power installed on the Faroe Islands will be in the range of 4 MW.

2.2 Energy consumption

2.2.1 Overview

Gathering energy consumption data for Nólsoy proved to be demanding. In contrary to Norway, there were no official statistics of energy consumption for regions, counties or municipals. On the other hand, the remote and well-defined energy system of Nólsoy could make possible a fairly accurate collection of energy consumption data.

Electricity

The electricity grid on the Faroe Islands is run by SEV, a municipality owned energy company with a monopoly of transferring electricity. Up to recently the monopoly also included production, but a recent change in the competition laws has opened the marked for other companies.

Electricity consumption for households is reported by the consumers once per year, making it easy to track the annual consumption, but a more detailed breakdown over the year is not available. More accurate consumption data could be obtained by recording the load on the island’s submarine cable, but this has not yet been commenced, and naturally such a study would have to go on for some time before reliable data could be obtained.

SEV has supplied statistics of the yearly electricity consumption on Nólsoy, sorted by trade for the most recent years.

Oil

Oil consumption data were not publicly available in the same extent as for electricity. The main reason for this is that in contrary to electricity, the oil sale is an open market with several competitors. For Nólsoy’s case, both Shell and Statoil had deliveries of domestic oil to private households the last years. Naturally they were reluctant to give away sales reports. There was also the dilemma of the privacy of the consumers to be considered.

Other energy sources

Other energy sources could typically mean solar power (thermal or electric), peat and wood (mostly drift-wood, since the Faroe Islands have few trees). None of these sources are monitored in any way, making it hard to estimate the amount of alternative energy sources consumed on Nólsoy. Nevertheless, these carriers are used in a limited extent, and therefore not included in this report.

2.2.2 Survey

Because of the limited knowledge about the energy consumption and the desire to obtain information on the building composition on Nólsoy, it was decided that a survey could be a good way to attain detailed user information, as well as confirming existing data. A survey could also be a tool to include and inform the local population in the planning process, something that was a high priority by the Vestnorden project group. Early in 2005, the author received a survey template created by Eva Rosenberg from IFE. With the help of two local contacts Bjarti Thomsen and Dávur Juul Magnussen, the survey was revised and adjusted for local conditions, as well as translated to Faroese. The complete survey with results can be found in appendix XXX. Below is a list of the key topics in the questionnaire with a brief description.

General building information

Type of house (single unit, row house), shape, size, heated area, year of construction and type of basement, if any. First of all, these data would help categorizing the buildings into different groups. In addition, they are needed for power demand calculations.

Heating methods

List of the household's heating methods and its power, including floor heating. Description of hot water boiler. These data will help map the heating infrastructure, an important information when considering substitute energy carriers.

Thermal insulation

Thermal insulation materials and thicknesses, number and area of windows and the number of layers in said windows. This information will mainly be used for heating power load calculations, but will also give important information about the insulations standards, and the possibilities for adding newer insulations as an energy-saving effort.

Electrical equipment

A list of the number typical electrical appliances, including light bulbs. An input factor in load calculations.

Energy consumption

The total energy consumption of the most common energy sources per year and for a typical winter/summer month. Data for other spaces, like boat houses and sheep cots have a separate post. The electricity and oil data can be checked against the supplier's numbers for consistency.

A contact was made with the island's primary and junior high school, who agreed to help with the organisation, distribution and collection of the questionnaires. On Friday the 28th of April, 2005 the surveys were handed out to every household and business on Nólsoy (see appendix II). A brief description of the Vestnorden project, as well as a two-page instruction was included. It was hoped that the information regarding the Vest-Norden Project and Nólsoy's part in it would motivate the inhabitants to fill in the survey. The survey was anonymous, but with a possibility for filling in name and phone number if the household agreed to be contacted in case of any questions.

The time limit for the survey was initially intended to be 1 week. The reason for this short deadline was the arrangement of a public information meeting late in the following week, and it was hoped that some initial data could be presented to encourage the completion of the survey for those who hadn't returned it already.

The first impression from the survey was that it took longer time to receive the completed forms than initially hoped. When the forms were picked up after scarcely a week, only 25 of about 100 households had completed the survey. This was lower than expected. The initial feedbacks received indicated that many people hadn't bothered to spend time on it yet, or were not finished. In retrospect, the design of the survey might have been one of the main reasons for this. The form covered one full page with two columns, and probably looked more complicated than it really was. It might have been wiser to skip some of the less important topics, for instance "Electrical equipment", and expanded the survey to two pages, making a "friendlier" design. Other sections could with advantage have been compressed, for instance the "Hot water" part, where type, installed power and age of the boiler could be written on one line instead of covering three lines. Such changes wouldn't degrade the information gained by the survey, but could probably have made it more "appealing" to start working on.

When the survey was considered complete after one month time, 35 questionnaires had been returned, of which 29 were for private households.

The completed surveys were added to an Access database for further study.

Survey results

Because of the limited number of businesses and public buildings on Nólsoy, this summary will only look at the household results.

Of the 29 households that returned the survey, 3 had to be turned down because of a lack of responses. The remaining 26 forms, corresponding to 25% of households on Nólsoy, were fairly well filled in, but most forms had some questions that were unanswered.

Below follows a short summary of the most interesting results from the questionnaire.

- **Type of building:**

Single-unit dwelling:	92%
Row house with one shared wall:	4%
Row house with two shared walls:	4%

Almost all households that turned in the questionnaire were single-unit dwellings. This doesn't seem to quite reflect the actual building composition on Nólsoy. One reason could be that young and middle aged people with families often live in bigger, single unit houses, while the smaller row-houses are habited by elderly people or used as a summer house, and that the first category is over-represented among the returned forms.

For comparison reasons, the building sizes will be sorted in four different categories following the standard of SSB, the Norwegian Statistics Department:

- **Building sizes (gross area):**

Below 60 m^2:	4%
60 - 99 m^2:	19%
100 – 149 m^2:	31%
150 m^2 and above:	46%

The high percentage of buildings larger than 150 m^2 is a result of the large share of single-unit dwellings present in the survey results.

The year of construction ranged from 1650 to 2005, but 90% of the buildings were built between 1930 and 1990. All in all the total average was 1949. The size of the heated area was in average 72% of the total gross area. All houses in the survey had a basement, but only 11% of those were heated.

Every house in the survey had an oil furnace, and only two households had electrical heating utilities, including one heat pump. Unfortunately the section about thermal insulation was lacking, but the stated insulation thickness in outer walls was spread out from 30 to 400 mm. Because the "Windows" section suffered from the same low response rate, there was little to comment on.

Since there will be no attempt in this thesis to estimate the household's theoretical power demand, the "Electrical equipment" section will not be addressed.

The average yearly electricity consumption of the households that participated in the survey was 4053 kWh, while the average yearly oil consumption was 2964 litres, corresponding to 29933 kWh. When divided by the heated area of each household, this corresponds to 39 kWh el per m^2, and 300 kWh oil pr m^2. For the net area the equivalent numbers are 29 and 219 kWh/m^2. In comparison, Norwegian households larger than 150 m^2 use in average a total of 171 kWh energy/m^2 gross (SSB, 2004).

2.2.3 Yearly energy consumption

Electricity

The electricity consumption is relatively easy to monitor, since the island under normal operation is supplied by a single, 10 kV submarine cable from the mainland. Table 1 shows the yearly electricity on Nólsoy by sector:

Sector	2002	2003	2004	2005	2006
Fish farms	1263360	1043040	34272	42024	44460
Public buildings	165710	160726	152862	158278	156108
Building activity	7782	7848	166	1196	2072
Fishery	8	92	894	4138	3974
Transport, post and communication	98672	102098	112806	97828	96460
Street lighting	70388	61096	75956	74326	74942
Trade, accommodation and restaurant	66736	62410	63118	75996	70770
Church and bethel	2578	2430	2850	2854	2878
Agriculture	4948	4636	4328	4078	4324
Culture and spare time	6652	5846	5214	6736	6324
Boat houses	4614	3994	3018	3110	3156
Households	842844	822302	900720	859424	876392
Reconditioning etc	1444	1240	1954	1184	1194
Total	**2535736**	**2277758**	**1358158**	**1331172**	**1343054**

Table 1 - Total yearly electricity consumption per sector, Nólsoy [kWh] (SEV)

As the data show, the electricity consumption was almost halved in 2004 as the local fish farm was shut down. Although there are several plans to reopen the business in some form, no definite decisions have been made. The 2006 figures are estimated consumption.

Nólsoy has two diesel generators as a backup for unexpected interruptions in the power, for example caused by damage to the submarine cable. The aggregates are two identical Mercedes Benz OM404A 320 kVA 256 kW, both connected to the island’s 400V distribution grid. One aggregate is sufficient to cover the power demand in most cases.

The backup generators are rarely used, but must be ready for operation as the submarine cable is a vulnerable spot in the electricity network. The inlet between Nólsoy and Torshavn is constantly being used as an anchoring ground for Russian trawlers unloading fish, and there have been incidents where anchors have damaged the cable, resulting in power loss and costly repairs.

One of the most important and complicated problem is to get an accurate estimation of the maximum total power demand. For electricity, this could be achieved by measuring the power flow on the island’s supply cable. For heating this is a more complicated issue, as there are currently no devices installed measuring the power on oil furnaces or other fuel-based heaters.

A more theoretical approach to the maximum power load issue would be to estimate these values using building data from the survey coupled with meteorological statistics for the Nólsoy area. Even with a simple approximation, this method can give a good estimation that can be adjusted against more accurate measurements of single buildings, and then applied to larger masses of buildings. To reduce the workload it would be necessary to categorize the building mass as much as possible, and accurate survey data would make this job a lot easier and more accurate.

Conclusion

The average yearly electricity consumption per household on Nólsoy in the period 2002-05 was 8395 kWh. The total electricity consumption average was calculated from the years after the fish farm was closed down, and corresponds to 1345 MWh.

Oil

The oil consumption on Nólsoy can roughly be divided into two sections, oil used for heating and oil used as propellant on boats, with the latter being only a small portion of the total.

There are several available data sources for estimating the yearly oil consumption on Nólsoy. SEV claims that a typical household on the Faroe Islands use approximately 4000 litres of oil each year, which corresponds to about 36000 kWh of net heating if the oil is burned with 90% efficiency. With approximately 100 habited households on the island, this would correspond to 400000 litres of oil yearly, not including the businesses and public buildings. This is a high estimation, compared to the fact that the average total energy consumption for Norwegian households in 2001 was 23000 kWh (single-dwellings 27500 kWh, SSB 2004). It should be taken into account that the Faroe Island’s climate is cool and that the number of degree days is high, but as a comparison, Oslo has in average 4177 degree days yearly, compared to Tórshavn’s 3600 (SSB 2005; Jacobsen). The high average wind speed could make the heating demand higher than the number of degree days suggest. Also, the heating systems on the Faroe Islands will have a long operating time at part load due to the cool climate, while in Oslo the heating demand is substantially higher in the winter and almost non-existent in the summer. This can result in lower fuel efficiency for the Faroese systems.

Because of the high electricity cost, the Faroe Island’s heating system is nearly solely based on oil combustion. Therefore it can be assumed that in general, a household’s heating demand equals it’s oil consumption, and vice versa. A good source for accurate numbers on the heating demand is the district heating network outside the capital Torshavn. The system is run by SEV, and supplies the customers with hot water supplied from a refuse incineration plant. Table 2 shows the average heating demand per household for the district heating customers:

2000	2001	2002	2003	2004	Average
21097	20679	19863	19726	19985	20270

Table 2 - Average heating demand, district heating customers [kWh]

Calculating “backwards” with a presumed 90% efficiency in an oil boiler system, the average heating demand corresponds to 2230 litres of oil per year. This is substantially lower than the 4000 litres SEV claims as a typical household consumption. One of the reasons for this relatively low heating demand can be that the houses connected to the district heating network are all new, and built with modern isolation standards. Many of these houses are row houses, reducing the heat loss further.

Initially the two companies selling heating oil on Nólsoy were reluctant to give out sales figures. This was partly for competitive and partly for privacy reasons. However, a couple of files were released. The companies are referred to as company A and company B.

1. The most comprehensive file was an Excel file with a register of almost 4000 different oil sales that company A delivered on Nólsoy from 1992 to 2005. Each file is registered with an anonymous customer number, date and quantity, and was sorted by customer. The file both includes households and businesses.
2. Company B provided a file with oil sale data from 2000 to 2004, broken up in monthly values. The numbers were divided into 4 sectors, private, commerce, ship and public.
3. The last document showed the total yearly sale from each company from the years 2000 to 2005.

Company A's oil sale figures were processed in Excel, and the total yearly sales were calculated. These values and the sum of the monthly values from company B's file were compared to the third file, the overview of total yearly sales. When compared, it turned out to be a substantial error between the sum up values and the total reported sales. The reason for this error is not known, but one possible reason is that the registration dates of sales could be different, since Nólsoy has a central storage tank used by both companies, and this tank's oil level could vary from year to year.

It would be interesting to separate the households' sale data from these numbers to compare them with the earlier estimations based on district heating statistics from Torshavn. Company B already had a separate post for household sales in file number 2, but company A's sale file, number 1, had no comments about customer type. When the total yearly sum from company A's file was added to the sum of company B's household category, the yearly sum was in the magnitude of 350000 litres yearly. Divided by approximately 100 households this would correspond to 3500 litres yearly. This figure is a bit under the 4000 litres/year estimation from SEV, but still a lot higher than the 2230 litres of oil equivalents consumed by the heating network customers.

Since the company A file most likely included sales to businesses and ships, an attempt were made to sort out the values that could not be a household purchase. Most domestic oil tanks usually contains in the region of 1000-2000 litres, a single oil purchase larger than 2000 litres would probably not have been to a private household. Therefore the Statoil purchase data were re-added, but this time only oil purchases below 2000 litres were counted. This had a considerable effect, reducing the yearly sum from between 11 to 19 percent over the 6-year period in question. When adding these numbers to the company B household data, the 3500 litres per household per year was reduced to 3000-3200. More specifically:

2000	2001	2002	2003	2004	Average
3241	3193	3105	2969	3114	3125

Table 3 - Annual oil consumption per household, Nólsoy (litres)

The average of 3125 litres corresponds to 28125 kWh if used at 90% efficiency.

Many of the houses on Nólsoy are fairly old, build early in the 20th century, and do not follow modern standards when it comes to insulation thickness and air tightness. This could partly explain the considerably higher energy consumption than for instance the new houses connected to the district heating in Torshavn.

Because of the time frame of this thesis, the simulation process had to be started before the survey results were collected. This means that the calculated value of 3125 litres was used as average oil consumption per households. Compared to the questionnaire results of 2964 litres per year, which is 5% lower, the estimation turned out to be acceptable.

Conclusion

The oil sale statistics provided makes it possible to establish very accurately the total yearly oil consumption. However it should be noted that the yearly consumption fluctuates substantially, and that the different data sources don't always give the same number. This could be a result of big purchases being registered in two different years in different sale statistics. Because of this, and average value of the five-year period in question would probably be the best estimation. The yearly sales and the average are shown in Table 4:

2000	2001	2002	2003	2004	Average
410452	576358	543004	401195	423720	470946

Table 4 - Total yearly oil sales 2000-2004, Nólsoy (litres)

The average of 470946 litres of oil corresponds to 4.66 MWh (gross).

2.2.4 Tap water

The energy consumption for tap water heating is included in the oil consumption figures, but in order to get input data for the simulation it is necessary to identify this specific energy quantity more accurately.

Direct heating of tap water as it is used is very power demanding when the flow rate and temperature is high. The most common solution is to use accumulation tanks for preheated water. This reduces the power demand, and at the same time introduces the possibility of using energy when it's readily available or especially cheap, in example during the night time.

For an ordinary household, hot tap water will contribute to approximately 30% of the total water consumption, corresponding to 66 litres per day per person (Hanssen et al, 1996). More specifically:

Low value	40 – 60 l/day/person
Medium value	60 - 100 l/day/person
High value	100 - 150 l/day/person

The energy consumption for tap water heating can be expressed with the following formula:

Formula 1

$$\mathrm{E} = q \cdot C_p \cdot \rho \cdot \left(T_{tap} - T_{source}\right) \cdot t$$

where:

q: Water flow [l/s]

C_p: Thermal capacity of water [4.19 kJ/kg]

ρ: Specific density of water [1000 kg/m^3]

T_{source}: Temperature of the tap water source [C]

T_{tap}: Desirable temperature of the tap water utilized [C]

t: Time [hours]

With Formula 1 the average energy consumption for tap water heating can be estimated. The hot water temperature for ordinary households usually lies in the interval of 50-80 degrees Celsius. The cold water is assumed to have a temperature of 5 degrees Celsius. Using these values, heating a quantity of 66 litres per person per day would require an energy consumption of 3.85 kWh/day per person. For a typical Nólsoy household, with an average of 2.7 persons, this would correspond to 3794 kWh/year. Other sources list average energy consumptions ranging from 2033 kWh/year (Larsen & Nesbakken, 2005) to 3-4000 kWh/year (Sørensen, 1977) per household for tap water alone.

3 System description

3.1 Distributed loads

The key duty of a wind-diesel system is to cover an instantaneous electric power load. However, the load and available wind-power will vary over the course of the year, resulting in shorter or longer periods when there is a mismatch between the available power and the load demand. The wind-diesel system is designed to be able to cover the maximum load, meaning that there will often be a surplus of power in periods of low load or high wind (or both). The excess load has historically been disposed of in a dump load in order to maintain the energy balance and a stable frequency and voltage on the grid. This leads to a low wind energy penetration, as well as low fuel efficiency as a result of the diesel generators being run on part-load.

In order to make wind-diesel systems more economical it is necessary to reduce the wind/load mismatch. This can be achieved by storing excess energy for later use, or use loads that can be varied according to the surplus power. Typical storage and loads for application in a wind-diesel system can be:

Storage:	*Thermal storage, water pumping, hydrogen production and storage, batteries*
Loads:	*Thermal loads, desalination, industrial load*

Some of these appliances can in fact be classified both as a storage device and as a load, in example thermal storage elements. Desalination and industrial loads were considered to be unrealistic for the Nólsoy case study, and will not be further addressed.

It could be convenient to separate the storage part into two different chapters, short-medium and long time storage.

3.1.1 Short to medium-time storage

Short and medium-time storage is designed to compensate for the imbalance between energy generation and consumption on an instantaneous, hourly or daily basis. Some of these energy storage devices are merely used to improve the quality of the delivered electricity and stabilize the grid, allowing diesel generators, fuel cells and electrolysers to start up and power down when needed. Such items include capacitors, flywheels and battery banks.

Additional storage devices can be added in order to improve the wind energy penetration and reduce component sizes. In a pure wind-diesel system, some form of storage is needed in order to maintain a reliable power supply in periods with low wind.

Another important purpose of energy storage is the possibility to even out the load on the power grid by shifting controllable electric loads to less busy hours, for instance in the middle of the night.

Hydrogen storage

Hydrogen storage in autonomous power grids is a relatively new but promising appliance. Hydrogen is produced by an electrically powered electrolyser, and stored, most commonly in compressed form. The hydrogen can then be used in a fuel cell or a hydrogen combustion generator for electricity production. A big advantage of this setup is the ability to store large amounts of high-quality energy over a long period of time.

Hydrogen storage is commonly divided into three different groups according to the technology in question:

Pressurized gas storage

The most commonly used technology for hydrogen storage is pressurized gas storage. Until recently these storage tanks have been fabricated from steel and aluminium with a typical storage pressure of 200-250 bars. Research in the field of composite materials has lead to the development of new tanks designed to withstand pressures up to 800 bars. These high pressures are however not feasible for large-scale storage because of the rapid increase in tank costs and the increased losses during compression.

Liquid storage

The hydrogen gas is cooled to -253 degrees Celsius, at which it turns liquid and stored in isolated tanks at atmospheric pressure. Liquefying hydrogen is a very energy intensive process, and energy corresponding to 28-40% of the liquid hydrogen's heating value is lost during the process. Another big drawback is the loss related to the vaporizing of the liquid hydrogen under storage. This loss will vary with the size and design of the storage tank. Typical loss values are from 0.4% per day for a 50 m^3 container to 0.06%/day for a 20 000 m^3 tank (Züttel).

Metal hydride storage

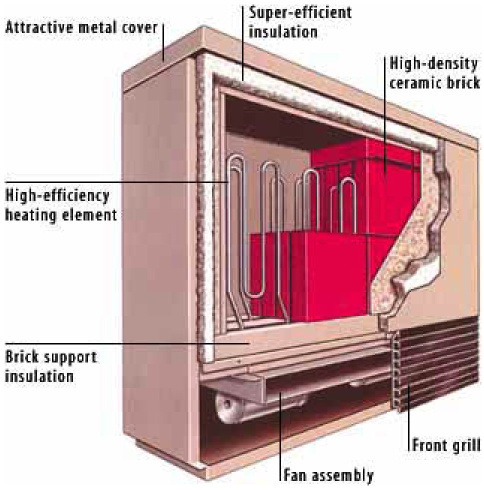
A chemical reaction binds the hydrogen molecules within a powder of metallic alloy, allowing a high energy density. One advantage with metal hydride storage is the low working pressure and low explosion and fire hazard. The biggest disadvantages are the low weight-density and the immaturity of technology. Great progress is being made in the field of metal hydride, and this is certainly an interesting technology for the future, especially in automotive applications.

Conclusion hydrogen storage

Hydrogen storage is a promising technology for storing high-quality energy in large quantities. The cost is however still too high, but is expected to fall sharply as the technology matures. Another drawback is the low power efficiency for the total chain, typically around 20%. However, with a good system design and a wind profile that matches fairly well with the power demand the amount of energy going through the hydrogen chain can be only a fraction of the total energy demand over the year. A few wind-hydrogen demonstration plants are operational, for instance the Utsira Project developed by Norsk Hydro.

Electric Thermal Storage Heaters

An Electric Thermal Storage heating unit (ETS) is a resistance heater with an electric element encased in ceramic blocks. When charging, the ceramic blocks are heated up to 1200 degrees. Air is then circulated inside the ETS, warming it to 180-200 degrees before returning it to the room. (Skrecc, 2006) The unit will then release the heat as needed for up to 12 hours, even when the electricity is turned off.



Electric thermal storage heaters are usually used in regions where the electricity is substantially cheaper during the off-hours, and can be equipped with a cooperative-installed load control device for centralized control of the unit. Units that are coupled with an air-source heat pump are also commercially available, greatly reducing the energy demand.

Classic room unit heating concepts typically range in sizes from 2.4 kW to 9.0 kW, with an installed cost from approximately $1200 to $1900 (CEC, 2006).

Thermal water storage

Thermal water storage (TWS) has traditionally been most commonly used with thermal solar collectors, but could also be useful in combination with other energy sources. In fact, a classic domestic hot water heater can also be viewed as a thermal storage unit with a primary goal of reducing the maximum power demand. While draining hot water the power consumption is often in the range of 15-20 kW, while the boiler's electric heat element could be only 3 kW or less (Rekstad, 2000). Another advantage is the possibility of adding more power than the current consumption, for instance from solar power or an incinerator with a fixed, optimal power.

Water has many properties making it well-suited for thermal storage. Its specific heat capacity is as high as 4.2 KJ/kg*K (1.16 kWh/m^3*K), nearly ten times as high as iron. Another advantage is the formation of different temperature layers in the storage tank. This ensures that the load always will be supplied with the hottest water available, and allows for sun-heated water to enter the tank on different levels according to its temperature.

As for ETS, thermal water storage units can be equipped with remote load control making it an excellent appliance for controlled energy storage. One of the biggest advantages of thermal water storage compared to ETS is its diversity. In a well designed system, a TWS can supply both tap water and water for space heating, each at its own temperature level.

3.1.2 Long-time storage

Long time storage can, depending on the configuration, be used to store energy on a time span ranging from a few days to seasonal variations.

Hydrogen storage

One of the advantages of hydrogen storage is the huge range in storage time span ranging from short to almost indefinable. Long time hydrogen storage will however most likely exclude one of the three most common storage technologies, liquid hydrogen storage. The reason for this is the substantial storage losses over time related to evaporation of the liquid hydrogen. These losses can be reduced a great deal for large scale storage, and has been reported as low as 10% annual for extremely large storage vessels (thousands of m^3). However, the size and investment costs of such tanks are not suitable for application in a stand-alone energy system.

Long-time thermal storage

Pumped hydropower

Pumped hydro storage is a technology most commonly used by the electrical industry in regions with a large share of thermal power plants. Thermal plants are ideally run at the rated power, and it is an elaborate and costly job to shut them down. This means that there often will be excess power available at night time, since the power demand is much lower than during the day. This is where the pumped hydropower comes into the picture. Operating as a normal hydropower station at the daytime, the plant has the ability to pump water back to the storage basin at night using low-priced electricity. At daytime it runs like a classic hydropower plant, drawing water from the basin and generating electricity for the grid.

Approximately 70% to 85% of the electrical energy used to pump the water into the elevated reservoir can be regained. The technique is currently considered the most cost-effective means of storing large amounts of electrical energy (Wikipedia, 2006).

3.1.3 Storage system design

For the Nólsoy case, a short to medium time storage element would be best suited to supplement a wind-diesel system. Primarily because there are no big mismatch between the wind and load profile throughout the year. Secondary because this case study has no ambition of creating a pure renewable energy system. The main goal is to reduce the island's dependency of fossil fuel in an energy efficient and economic way.

Of the short to medium time storage systems, the two different technologies considered were hydrogen storage and the thermal storage. After careful consideration, the choice fell on a thermal storage system. Hydrogen systems have many possibilities in renewable energy systems, but also some disadvantages that made them less suitable for the Nólsoy case. The main reasons were the energy consumption profile and the already mentioned objective of the Vestnorden project. Hydrogen technology stores high quality energy for conversion back to electricity, but when almost 80% of the energy consumption on the island is based on combustion of fossil fuel, the high cost and low system efficiency of a hydrogen system is not fitting the scenario well. Instead of decreasing the diesel consumption of the electricity generators, the gain of substituting parts of the thermal demand will be much greater from both an environmental and a cost of energy point of view.

Of the two mentioned thermal storage technologies, the Thermal water storage is best suited for Nólsoy, since virtually every household has a water-based heating system.

3.1.4 Control and communication technology

This section will give a summary of some of the most suitable communications technologies for a distributed load system on Nólsoy.

The main goal for the load controller is to distribute the excess wind power as equally as possible to the distributed loads. This is performed by switching the loads on and off as the available energy varies. In order to switch the loads, a command signal has to be transferred from the load controller to the individual distributed units. The following components are needed to perform this operation:

1. A distributed load controller that computes and processes the control commands. The controller must have a communications interface to both the central controller and the distributed loads. This communication can be either one or two-way, and needs to have the necessary transmitting rate to handle the complexity of the control signal.
2. A unit at each distributed load that can receive and intrepid the control signal sent by the load controller, and control the load accordingly. For a two-way system the unit must also be able to generate and transmit a return signal.
3. A communication carrier.

The most relevant communication carriers are

- Wireless radio
- Powerline Carrier
- Cable
- Fiber Optics
- Telephone line

(Johnson et al., 2002)

Wireless radio and powerline carrier were considered to be most promising technologies for the Nólsoy system.

3.1.5 Powerline Carrier

Sending the control signal over the power grid has been used for many years in load control applications. By connecting low-frequency radio transmitters connected to the conductors, it is possible to transmit data with a speed up to several hundred Mbit/s (Wikipedia, 2006). An advantage with the Nólsoy power system is that the whole island is covered by the same low-voltage grid, meaning that the ripple signal does not have to be transmitted past any transformers. This means that a two-way communication over the power line is possible with at relatively low price.

3.1.6 Wireless radio

Radio transmission is a simple and robust option and that is getting more and more popular, especially for computer networks. The technology offers two-way communication. The specification and cost of the antenna and transmitter will depend on the range and terrain between the load controller and the unit. Nólsoy has currently a central wireless network transmitter that offers a high-speed internet connection, and there is a possibility that this setup also can be used for load control communication.

3.2 *Input data*

3.2.1 Wind power

The opening of this chapter is based on chapter 4 of "Decentralized energy supply based on renewable energy sources", 2005, by the writer.

The Faroe Islands climate is greatly influenced by the Gulf Stream, which makes the weather humid and windy with cool summers and mild winters. The numerous hilly islands are causing considerable local winds, as a result of stowing, channelling and turbulence. Frequent passing of cyclones contribute to the unstable weather conditions, with rapid pressure drops causing damaging high wind speeds. The wind speed during a cyclone can reach as high as 40 m/s, with gusts up to 70 m/s. Average wind speeds are commonly in the range of 6-10 m/s depending on the location. Gales are common during the autumn and winter, usually blowing from west and south west. The wind speed is generally higher during the winter than the summer. Though the general climate is very windy, calm periods do occur, most often in midsummer, but then only for very short periods (Cappelen & Laursen, 2004).

There have been no long-time wind measurements on Nólsoy, but in 1989 an attempt was made to correlate short-time wind series recorded on the island with wind series recorded in the vicinity. Unfortunately the recordings only proceeded for two month.

In connection with part two of the Vestnorden project it was decided to initiate a long-time wind measurement on the island. After some delay the measuring mast was raised in the spring 2006, and the first data was collected the 10th of March. Figure 5 shows a plot of the measured wind speed of March 2006.

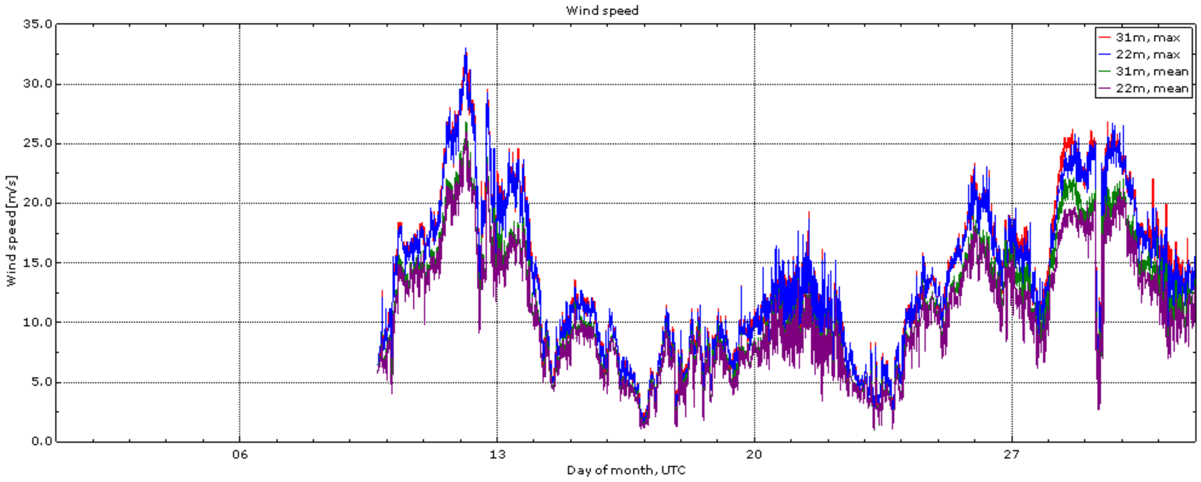


Figure 5 - Wind speed March 2006, Nólsoy Wind Station (Risø/Wind-Røkt)

Due to the time span of this thesis, the recorded wind data were limited. As a compromise, a three month series of 10 min mean values were correlated with a wind series from Mykines, a meteorological station on the Faroe Islands. This work was done by Andreas Rinnan at IFE. As can be seen in Figure 5, the wind speed on Nólsoy is high. The mean wind for the first three months of measurements from the wind station was 9.39 m/s at 30 metres height, and the yearly mean wind speed for the correlated wind series was 9.82 m/s.

3.2.2 Load profiles

Electricity

The method used for generating an electric load profile was similar to the procedure explained in (Lemgart & Ulleberg, 2005):

1. Find the yearly load profile, sorted by average monthly consumption.
2. Find a representative normalized 24 hours load profile.
3. The specific load for any hour of the year can be found by multiplying the month's average consumption with the current hour's normalized load.

Finding the yearly load profile for the electricity consumption proved to be challenging. The energy company SEV could not provide any detailed graphs or statistics. In contrary to Norway, where the electricity consumption is often reported on a quarterly basis, all private consumers on the Faroe Islands only report once a year. The best information that could be obtained was a claim from SEV that the electricity consumption in general was twice as high in the winter as the summer.

In order to obtain a yearly profile it was decided that the average outdoor temperature would serve as a basis for the curve form. Energy consumption and outdoor temperature are in many ways connected, even though little electricity is used for heating on the Faroe Islands.

In order to obtain a higher resolution on the load profile an attempt was made to divide the yearly profile into weekly values. The reference temperature was only available on monthly values, so a seventh-degree polynomial function was used to estimate each weekly load ratio. The total profile with 52 weekly load ratios was normalized to ensure an easy integration with the simulation model. The lowest value occurred in week 31, the last week in July, where the load was 55% of the maximum, which occurred in week 1. This fit in well with SEV's allegation of the summer load being half that of the winter.

The problem of limited available data reoccurred when the daily load profile was being investigated. The only available information was a three days plot of the voltage and current in the sub sea cable connecting Nólsoy with the main land, shown in Figure 6.

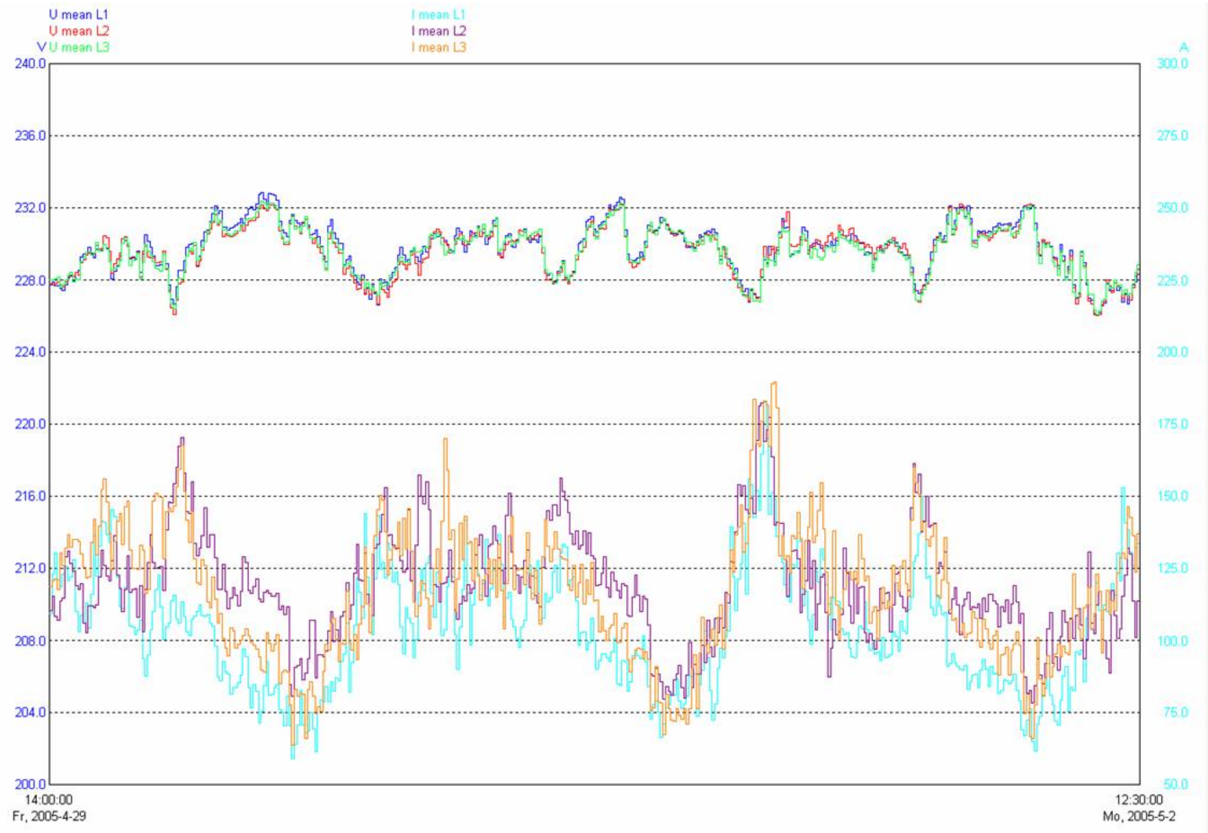


Figure 6 - Voltage and current plots from Nólsoy's electricity supply cable (SEV)

The source data for the plot was not available, so the different hourly loads had to be visually collected directly from the plot. The normalized 24 hours load curve is shown in Figure 7.

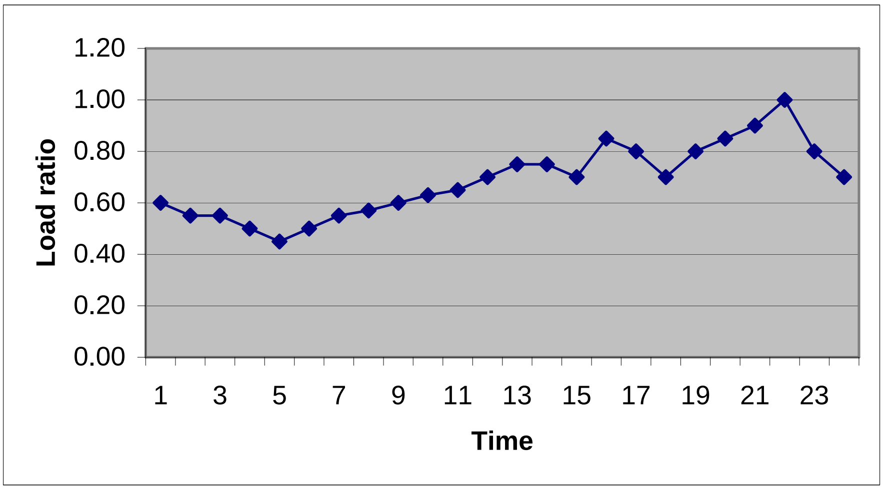


Figure 7 - Normalized 24 hours electric load, Nólsoy

The ratio of maximum daily load divided by the minimum daily load is 2.2. This ratio and the shape of the load curve consistent with measured load series from Grímsey, Iceland (Lemgart & Ulleberg, 2005).

Heating

The load profile for the heating demand follows the same pattern as the electricity profile, as it is highly dependant on the outdoor temperature. Since there was no additional information available, the weekly and daily profile was assumed to be equal with the generated electricity profile.

3.3 Simulation Software

The following chapter gives a short introduction of the simulation software and the model types used in the simulations.

3.3.1 TRNSYS

TRNSYS is a transient systems simulation program with a modular structure, based on FORTRAN subroutines. Originally a joint project between the University of Wisconsin - Madison Solar Energy Lab and the University of Colorado Solar Energy Applications Lab, TRNSYS has been developed since the early 70s. The current version, TRNSYS 16, was released in 2004. One of the advantages of TRNSYS is its huge library of models, and the possibility to develop new models and add them to the package.

More than 30 years after it was first released, TRNSYS is still being developed by the University of Wisconsin, as well as several other international institutions. A library of over 400 different components has been added by developers and users.

3.3.2 HYDROGEMS

HYDROGEMS is a library of computer models for simulation of integrated hydrogen systems based on renewable energy. HYDROGEMS is a result of more than 7 years of modelling and simulation work performed at the Institute for Energy Technology (IFE). The models are written in FORTRAN code, and are intended to be used with simulation programs like TRNSYS and EES (Engineering Equation Solver), but there are also standalone versions available. The library consists of models for power producing equipment, water electrolysis, storage systems and control systems. Because of its generic design, system parameters supplied from manufacturers or obtained from experiments (such as a U-I curve) can be read to the models from an external file (HYDROGEMS, 2005).

3.4 Types

This section will give a brief description of the TRNSYS types used in the simulation, and their key parameters. The different types are described under the system they are first employed, but system-specific settings are listed for every scenario.

3.4.1 Reference system

The reference system for Nólsoy used in this project is somewhat different from what is currently operating. Today, the island's electricity is delivered through a 10 kV AC sea cable connected to the main grid at Hvitanes, close to the capital city of Torshavn. At Nólsoy, the voltage is transformed down to 0.4 kV with a 400 kVA transformer, and fed into the local distribution grid. Two Mercedes Benz OM404A diesel generators (DEGS) with a rated power of 250 kW each (check this) serve as back up power should the mainland connection fail. The

DEGS are connected to the distribution network by 320 kVA transformers, one for each generator.

The system configurations proposed in this paper are assumed to run as a stand-alone system, unaffected by the central electricity grid. In order to quantify the fuel savings for these configurations, it would be useful to compare these against an isolated power system based on local diesel generators, rather than a grid-connected system. The base-case for Nólsoy is therefore chosen to be a stand-alone power system based on DEGS, and the central grid connection is neglected.

Equation block

Equations can be defined directly within the input file by using an equation component. These equations can be used as inputs to other components, as parameters and as initial values of inputs. An equation box can be linked to or linked from like a normal component, but rather than being represented in the generated input file by a UNIT or TYPE statement, the information contained will be placed in an EQUATIONS statement.

Type 9: Data Reader for Generic Data Files

This component serves the purpose of reading data at a regular time interval from a data file. The data is converted to the desired unit and can be used by other TRNSYS-components as time-varying force functions. Developed by the Solar Energy Laboratory, University of Wisconsin-Madison.

Type 120: Diesel Engine Generator Set (DEGS)

This model is an empirical description of a diesel engine generator set where the fuel consumption is expressed as a function of the normalized power output. The model can either be supplied with a fuel consumption curve for a specific DEGS or used with the generic model, suited for power ratings from 5-500 kW.

The generic model extrapolates from a reference fuel efficiency curve (average of 5 different DEGS), and incorporates a correction factor derived from measurements of 20 remote area power systems. Electrical and fuel efficiencies are calculated. The default fuel is liquid diesel, but the model can also calculate the equivalent flow rate of 5 different fuels, including natural gas and hydrogen.

The model is developed by Øystein Ulleberg, Institute for Energy Technology, and was originally included in the HYDROGEMS library.

Type 102a: Control functions for Diesel Engine Generator Sets

This model contains the control function for one or several diesel engine generator sets (DEGS) operating in decentralized power mini-grids. The DEGS are controlled in a master-slave setting, meaning that generator *i* can only be turned on if generator *i-1* is already on. For each DEGS, the load power where it switches on and off can be specified. All DEGS are assumed to be identical, and all active DEGS run at an *equal power output*. The model is written by Øystein Ulleberg, IFE.

3.4.2 Wind-Diesel

This is a typical configuration for stand-alone systems with renewable energy penetration. On a site with good wind condition, the fuel savings of the DEGS can be substantial. One disadvantage of this system is that parts of the wind energy have to be dumped due to the lack of an energy storage element.

Type 90: Wind Energy Conversion System (WECS)

The type 90 model calculates the power output of a WECS based on a power versus wind speed characteristic loaded from an external file. The model also takes into account the impact from air density changes and the wind speed increase with height.

3.4.3 Wind-Diesel-Domestic Hot Water Tank (DHT)

Type 4a: Stratified Storage Tank, Fixed Inlets, Uniform Losses

This type models a stratified storage tank with N (N <= 15) fully mixed layers of equal volume. This instance of Type 4 models a stratified tank having fixed inlet positions defined within the code. Fluid entering the hot side of the tank is added to the tank node below the first auxiliary heater. Fluid entering the cold side of the tank enters the bottom node. The model optionally includes two electric resistance heating elements, subject to temperature and/or time control. The control option allows the addition of electrical energy to the tank during selected periods of each day (e.g., off-peak hours). The auxiliary heaters employ a temperature dead band. The heater is enabled if the temperature of the node containing the thermostat is less than (Tset - Tdb) or if it was on for the previous interval and the thermostat temperature is less than Tset.

4 System design and behaviour

4.1 Establishing a base case

The first step of the simulation process was to build a model of the basic energy system of Nólsoy. In its simplest form, this energy system only consists of two basic components, an energy source and a load.

4.1.1 Energy source

There are numerous energy sources and carriers utilized in the energy system of Nólsoy, the most common being fuel oil, gasoline, gas, wood and peat. The initial studies will be limited to the electricity consumption only. In practice, this electricity is supplied by a submarine cable from the mainland. Since the island of Nólsoy will be considered an isolated energy system for the bulk of the simulation, a local electricity production unit would have to be added. Currently, two diesel generators serve as a back up system should the island's grid connection fail. Diesel generators will be used as base-load power source throughout the simulation. For stand alone power systems, diesel generators have served as a foundation for numerous of energy systems, and will continue to do so in the future. Diesel generators are reliable and relatively cheap in acquisition, but the rise of fuel prices have resulted in a sharp rise in operation cost. Other disadvantages with diesel generators are the discharge of green house gases, and low efficiency on part loads and with varying operating conditions.

Since one of the motivations for the Vestnorden project was to try to reduce Nordic island state's dependency of fossil fuel, an alternative renewable energy source had to be considered. Based on the unique climatic conditions in the region, wind power was chosen to be the main source of renewable energy. Naturally it is hard to design an energy system where wind power is the only energy source, primarily because of the fluctuations of the wind speed. Therefore a combination of wind and diesel energy will serve as the source of electric energy for most simulations.

4.1.2 Loads

The load represents the energy used by households, businesses and other consumers on Nólsoy. It is important to specify the types of energy or energy carrier each load consumes, since not all types can be substituted by each other. Thermal energy can for instance not generally cover an electricity demand.

Since the base case energy source is purely electric, the load will initially only represent the electricity demand on Nólsoy.

4.1.3 Creating the model

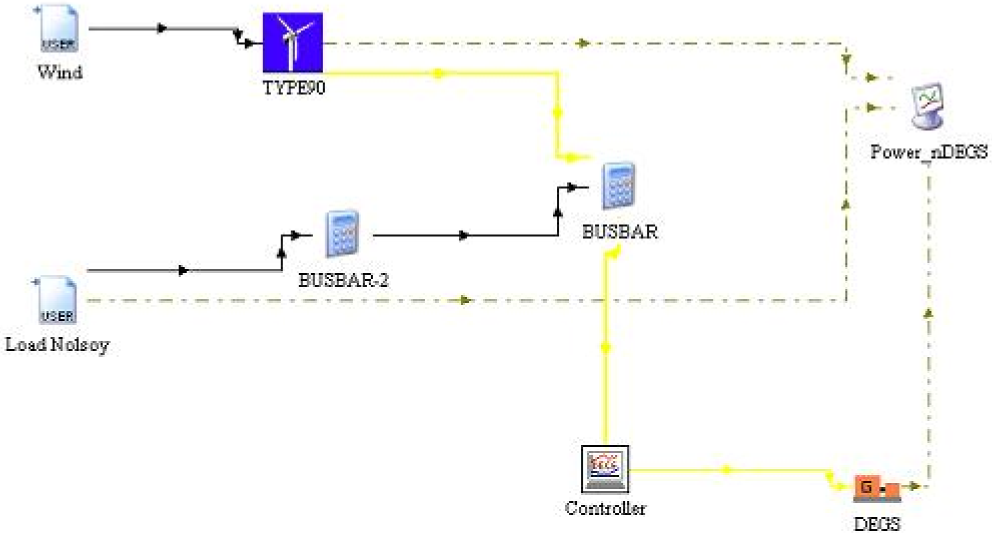


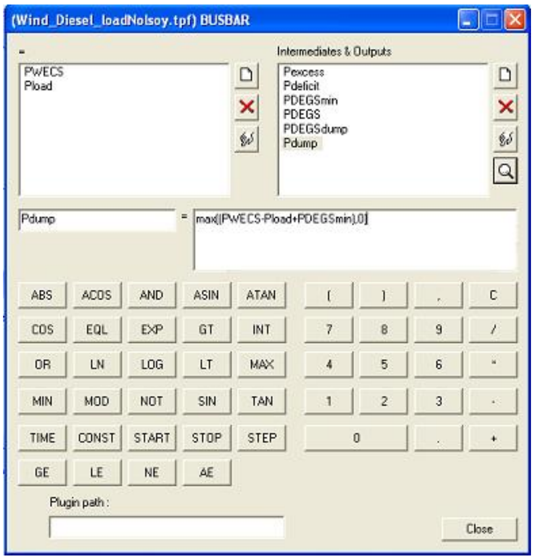
Figure 8 - Base case model of Nólsoy

Figure 8 shows the base case model of Nólsoy. The model has two inputs, a wind series and a load profile, shown to the left of the picture. The wind series is a list of hourly mean wind speeds that is representative for Nólsoy's wind regime. These data are fed into the Type 90 WECS model, where the electricity output is calculated according to the windmill chosen in the model configuration. Likewise, the electric load profile, consisting of hourly values of the average electric load, is converted to the correct denomination in "BUSBAR-2" and directed to the equation block "BUSBAR", together with the power output from the WECS.

Control system

The busbar is the heart of the simulation model. In short, it contains the equations that balances the energy system and makes sure the energy demand and energy supply match. Figure 9 shows the control window for the component. The left window contains the input and the right the equations and outputs. Each time step the following commands are performed:

1. *Pload*, the user load, and *PWECS*, the wind power production of the time step is collected from inputs.
2. The wind power production is compared with the electric load. If the production is higher, the difference is stored in the *Pexcess* variable; else the shortage is stored as *Pdeficit*.



(Wind_Diesel_loadNolsoy.tpf) BUSBAR

PWECS
Pload

Intermediates & Outputs

Pexcess
Pdeficit
PDEGSmin
PDEGS
PDEGSdump
Pdump

Pdump = max((PWECS-Pload+PDEGSmin),0)

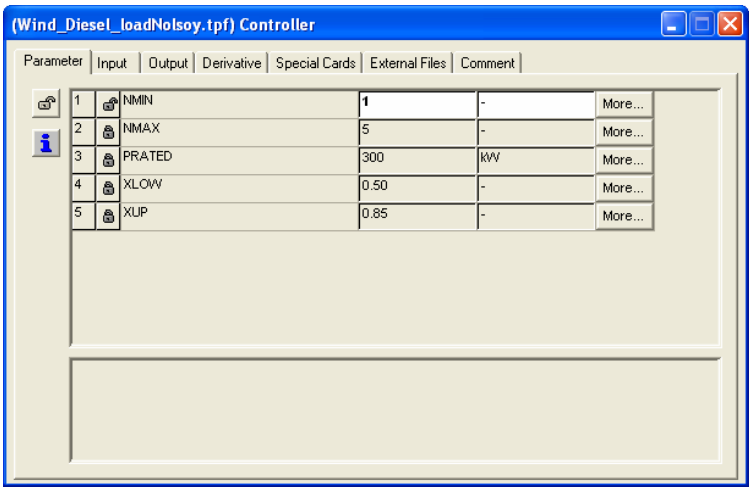
Figure 9 - Control system

3. If there is a shortage of power, the desired power output from the diesel generator to obtain balance is calculated and sent to the DEGS unit (*PDEGS*).
4. If the power from the windmill exceeds the load, the excess power (*PWECS-Pload+PDEGSmin*) is calculated and stored as the variable *Pdump*, the amount of

excess power that must be dumped in order to keep the energy balance. *PDEGSmin* is the minimum idling power output of the diesel generators in operation.

Diesel controller and mathematic model

The diesel controller takes the power demand object (PDEGS) and decides, based on the controller settings, the appropriate control strategy for the next time step. Figure 10 shows the settings for the controller. The adjustable parameters are:



1	NMIN	1	-
2	NMAX	5	-
3	PRATED	300	kW
4	XLOW	0.50	-
5	XUP	0.85	-

Figure 10 - Diesel Controller

***NMIN, NMAX*:** Determines the minimum and maximum numbers of diesel generators operating in parallel. Note that if *NMIN* is set to 1, one generator will always run regardless of the power load.

***PRATED*:** The rated power of *each* DEGS.

***XLOW, XUP*:** Defines the "call up" and "call down" power levels, the load power at which the corresponding DEGS is respectively switched on and off. If the power demand is higher than the maximum power output for the DEGS multiplied with *XLOW*, then a new DEGS is switched on. Likewise, if the power demand is lower than the max power of the DEGSs multiplied with *XUP*, one generator is switched off.

The controller has two outputs, *PDEGS*, which sets the power point for a single DEGS, and *NDEGS*, the number of DEGS required to meet the load.

Simulation outputs

In order to retrieve information from the simulation, outputs from each component can be connected to one or more output types. These types include integrators, printers, plotters and simulation summaries. For the base case, an online graphical plotter was added in order to visualize the power consumed or generated in the different components.

Figure 11 shows a print of the simulation results for a whole year. Note that the input data are artificially generated, and not from Nólsoy. The red graph displays the electric load, the blue the wind power and the pink displays the diesel generator power.

In addition to the plotter, an integrator with a file writer was connected to the most interesting outputs. The integrator was configured to display the cumulative sum each month for each input. The results are written to a *.out file that can be opened in most word processors, including notepad.

4.1.4 Configuring the model

The fabricated input data from the initial simulation had to be replaced with load and wind data generated for the Nólsoy case study.

The diesel generators currently installed on Nólsoy are not fitted for a stand-alone system. Instead, the DEGS controller was configured for diesel generators with a rated power of 100 kW, a minimum idling power of 40kW and a maximum allowable power of 120kW. The numbers of DEGS were not set, meaning that if more power is needed, another generator is started. With a maximum power load of 265kW, this means that if the max power load occurs at a time with zero production from the windmill, there will be three diesel generators operating.

The effect on system performance by changing the DEGS' rated power will not be investigated for the base case, but it is a highly relevant parameter for a system optimization.

The windmill used for the simulation is the Bonus 300 with a rated power of 300kW. As for the DEGS, the WECS will remain unchanged for the base case configuration.

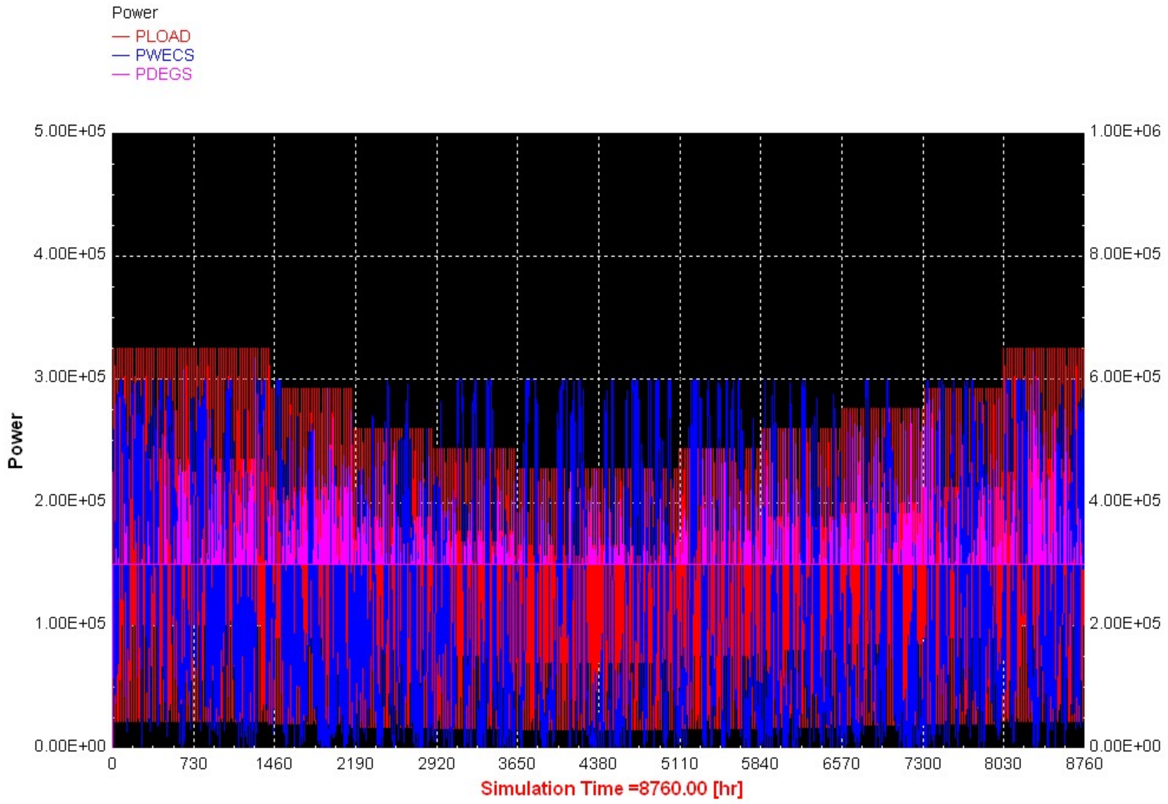


Figure 11 - Simulation plots from TRNSYS

The load series is a combination of a hourly 24-hour load profile and a long-time average varying with the seasons. One of the challenges is to make sure that the maximum power load and the total yearly energy consumption (the integral of the hourly series) match. Initially, SEV, the power company running the electricity grid claimed that the maximum power load on Nólsoy was 110kW. However, the annual electricity consumption of 1.35GWh corresponds to an average load of 154kW, meaning the max load must be much higher. Seasonal variations will also affect the maximum load, and the electricity consumption on the Faroe Islands is in average about twice as high in the winter than the summer (SEV 2006).

When compensating for seasonal variations and a fluctuating daily load profile, the normalized maximum load would have to reach 265 kW in the coldest week of the year (first week of January) in order to attain a yearly energy consumption of 1,35GWh. It is important to specify that this is the normalised hourly load, and not equal to the electrical design load of the system, since the short time load could reach substantially higher.

4.1.5 Simulation results

When running the base case simulations, the number of windmills in the WECS type was set to zero. The diesel generators would then cover the complete electric load, and it would be possible to obtain reference fuel consumption for a pure diesel system. Table 5 shows the most important outputs from the simulation.

E_{LOAD} [MWh]	E_{DEGS} [MWh]	E_{WECS} [MWh]	Q_{FUEL} [litre]	E_{DUMP} [MWh]	$E_{DEGSdump}$ [MWh]
1366	1366	0	421780	0	0

Table 5 - Simulation outputs, base case

Q_{FUEL} is the total fuel consumption of the diesel generators through the whole year in litre, and E_{DUMP} and $E_{DEGSdump}$ are the amount of total surplus electricity and surplus electricity produced by the diesel generators, respectively. Because all active diesel generators run at the same power and reduce the power output when a new generator is started, the $E_{DEGSdump}$ variable will remain zero.

The electricity consumption E_{LOAD} is in the same magnitude as the annual consumption on Nólsoy the last years (1358 MWh in 2004 and 1331 MWh in 2005). The diesel generators covered the total demand without any deficits.

Dividing the total annual electricity production with the generators fuel consumption gives an electricity generation of 3.24 KWh per litre of fuel. When using the lower heating value of diesel, 36.5 MJ/litre, this corresponds to a fuel efficiency of 32%.

The diesel price has followed the crude oil prices to a record high level the recent years. Currently, one litre of diesel fuel costs approximately 0.8 euro (Shell 2006). This would correspond to a COE (cost of energy) for the base case, considering the fuel cost only, of 0.25 euro/kWh. In comparison, the electricity price to private consumers on the Faroe Islands is currently 1.11 Danish kroner per kWh (0.15 euro/kWh) (SEV 2006).

4.2 Scenario I: Wind-Diesel

The setup for this scenario is similar to the system illustrated in Figure 12. Electricity produced by the windmill is utilized by the end users, supported by diesel generators should the wind power be insufficient. In this setup, one diesel generator is always running to ensure a stable and reliable grid operation. In reality, other power conditioning utilities like condenser banks, flywheels and power electronics might have to be added to ensure acceptable voltage and frequency levels. Grid stability issues will not be thoroughly discussed in this thesis.

Since the WECS type was already an integrated part of the base case model, no major adjustments had to be made in order to run the wind-diesel simulation. The number of windmills was changed from 0 to 1 in the WECS type, and the simulation was run. Table 6 summarizes the initial simulation for the Wind-Diesel system.

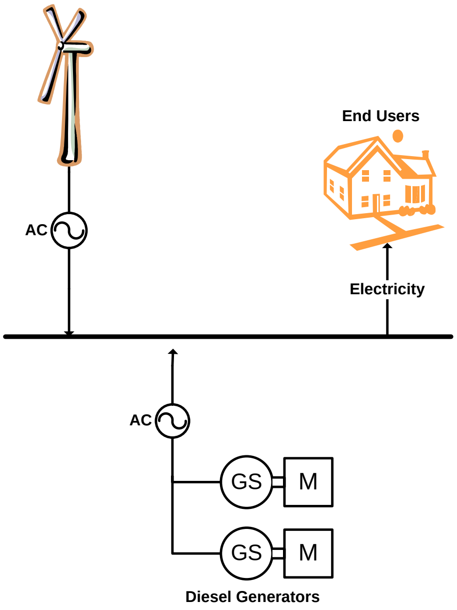


Figure 12 - Wind-Diesel setup

E_{LOAD} [MWh]	E_{DEGS} [MWh]	E_{WECS} [MWh]	Q_{FUEL} [litre]	E_{DUMP} [MWh]	$E_{DEGSdump}$ [MWh]
1366	587	1545	189395	766	215

Table 6 - Simulation outputs scenario I

It should be taken into consideration that the component sizes are not optimized.

Some comments on the results:

- The wind power production was 1545 MWh, 179 MWh higher than the total electrical load. However, only 779 MWh (50%) of this could be utilized by the consumers, mainly because the periods where the wind production exceeded the load. This resulted in an E_{DUMP} of 766 MWh, corresponding to more than 56% of the total annual consumption.
- The diesel consumption was more than halved compared to the base case; more specifically it was reduced with 189395 litres. Because of the minimum idling power of the diesel generators, 215 MWh of electricity produced by the diesels had to be dumped when the wind power was high enough to cover the load demand. The amount of dumped electricity from the DEGS corresponds to approximately 66 000 litres of fuel, nearly 35% of the yearly consumption.

Figure 13 shows the simulation output on a monthly basis. The blue bar, E_{LOAD}, displays the total electricity demand each month, the red, E_{WECS}, the total production from the windmill and the yellow, E_{WECS} utilized, the amount of the wind power production actually utilized by the load.

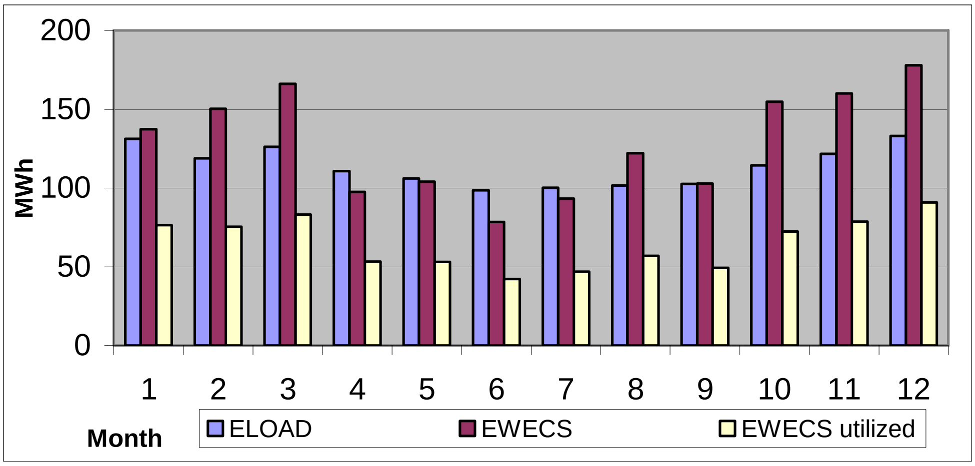


Figure 13 - Simulation outputs scenario I, per month

The graph shows how the wind power production is substantially higher in the autumn and winter months due to higher wind speeds. This matches the seasonal load variations well. An interesting point is that E_{WECS} *utilized*, the utilized amount of energy relative to the wind power production, is remarkably stable. This is displayed in Table 7:

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Des**
$\%_{EWECS}$	56%	50%	50%	55%	51%	54%	50%	47%	48%	47%	49%	51%

Table 7 - EWECS utilization ratio, scenario I

4.3 Scenario II: Wind-Diesel-DHT: Tap water

One of the biggest challenges with a wind-diesel system is to raise the amount of utilized wind power. The lack of storage element requires a good match between the electric load and the wind series. Adding an energy storage element to the system can greatly increase the system performance and wind power payload efficiency.

The motivation for introducing a hot water tank in this configuration is the possibility to reduce the loss related to over-production of electricity in periods with high wind and low electrical load. In a Wind-Diesel-DHT system, excess wind energy can be diverted to distributed hot-water boilers and converted to thermal energy. As well as covering simultaneous thermal load, the energy can be stored for later use with relatively small losses. Although converting electricity to low-temperature heat greatly degrades the quality of energy, this is a cheap and effective method of storing energy that otherwise would have gone to waste.

A domestic hot water system could typically serve 1-10 households with tap water, and possibly also supply water-based space heating.

Large loads of deviated power (on/off), such as water heaters and pumps, can give frequency and/or voltage problems in small distributed power systems. One way of reducing this problem, and possibly make the grid more robust, is to actively control electric loads. A cooperative control strategy can be used on deviated loads, meaning that it is possible to turn on hot-water boilers only when excess wind power is available, and internate between the loads to ensure an even distribution of energy.

The wind-diesel-DHT setup is based on the wind-diesel model in scenario I. But where the *PDUMP* variable represented excess energy that was dumped in scenario I, the idea is now to utilize this energy in distributed hot water tanks (DHT). Figure 14 shows an overview of the simulation setup.

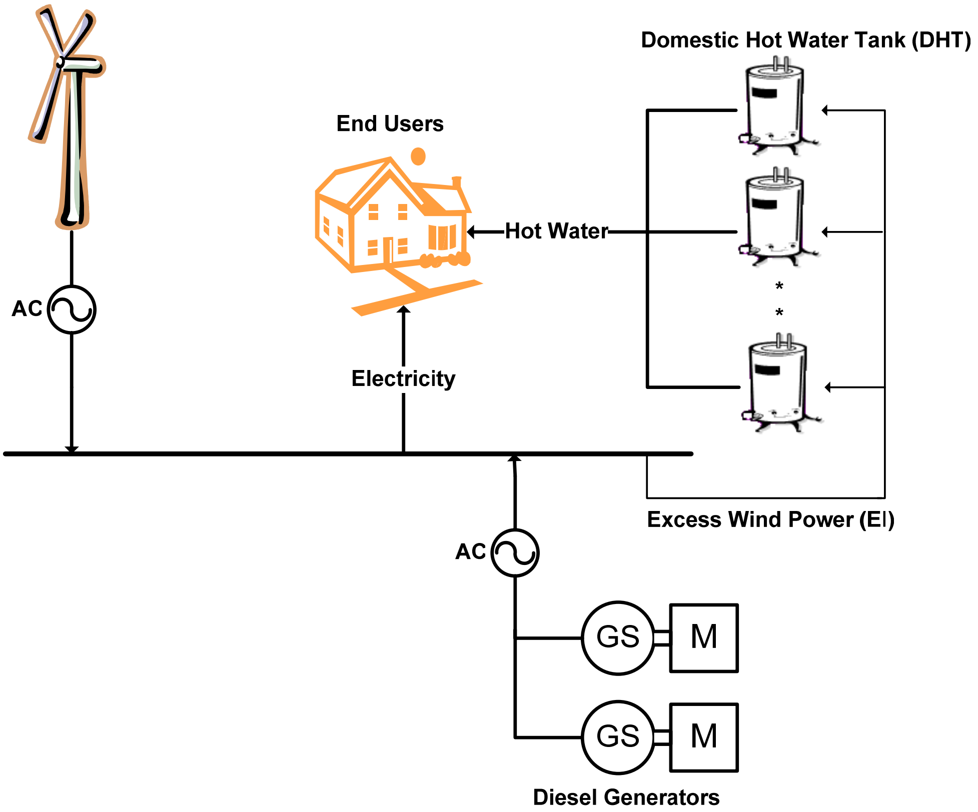


Figure 14 - Wind-Diesel-DHT setup

Since the electricity demand is already covered, the excess energy will now be despatched to a separated thermal load controller. More specifically, the excess energy can be described as:

$$Pdump = \max((PWECS - Pload + PDEGS\min), 0)$$

where $PDEGS\min$ is the minimum idling power of the diesel generators.

Thermal load controller

The thermal load controller unit is built from an "Equation Unit" type, and is the heart of the thermal energy system. It receives an input with the available excess power *PDUMP*, and by the means of the DHT rated power, the number of DHTs and the current priority system, decides which DHTs that should power on. The outputs to the DHTs are a binary signal with either "1" for power on, or "0" for power off.

In order to decide what DHTs to prioritize, the controller can receive a priority signal for each DHT as an input. The *n* different DHTs must each have a unique priority, ranging from "*n-1*" for the highest prioritized boiler to *"0"* for the lowest. The routines for prioritizing are solely based on the tank temperature, meaning that the DHT with the lowest tank temperature will receive the highest priority.

When a priority is received, the thermal load controller calculates how much excess power the unit has available, and if this power exceeds the DHTs rated power, the unit is switched on. Formula 2 shows the equation for calculating the available power. In short, it checks the priority level of the DHT with an equal (eql) function, and if it matches the particular priority in question, the *PdumpUnit* gets set to the corresponding power.

Formula 2

$$PdumpUnit_n =$$

$$\sum_{i=1}^{j}(eql(DHT_n\_pri,(j-1))\cdot(Pdump\cdot PdumpUnitRatio))$$

$$+(eql(DHT_n\_pri,(j-2))\cdot(Pdump\cdot PdumpUnitRatio-P\_DHT))....$$

$$+(eql(DHT_n\_pri,0)\cdot(Pdump\cdot PdumpUnitRatio-(j-1)\cdot P\_DHT)$$

where:

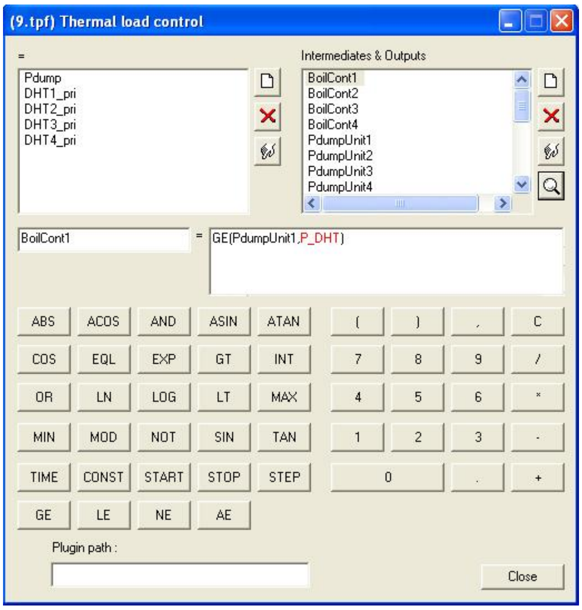
DHT_n_pri:	*The priority level for DHT $_n$*
Pdump:	*The total excess power available*
PdumpUnitRatio:	*The ratio describing how much of the excess power that is available per DHT. Default value is (1/number of households).*

The control signal function is based on the *$PdumpUnit_n$* variable, which was set in Formula 2, and is very simple:

$$BoilCont_n = GE(PdumpUnit_n, P\_DHT)$$

If the *$PdumpUnit_n$* variable is greater or equal (GE) to the *P_DHT*, the control signal is set to 1, else it is 0.

Figure 15 shows the Thermal load control equation block. The left box shows the inputs, the *Pdump* unit from the central control system, as well as a priority signal for each of the four connected DHTs.



(9.tpf) Thermal load control

=

Pdump
DHT1_pri
DHT2_pri
DHT3_pri
DHT4_pri

Intermediates & Outputs

BoilCont1
BoilCont2
BoilCont3
BoilCont4
PdumpUnit1
PdumpUnit2
PdumpUnit3
PdumpUnit4

BoilCont1 = GE(PdumpUnit1,P_DHT)

Plugin path :

Figure 15 - Thermal load control

DHT subsystem

The DHT subsystem consists of a load, a combined storage tank and water heater, a reheating coil and equation blocks. Figure 16 shows a visualisation of the cycle.

Heat load converter

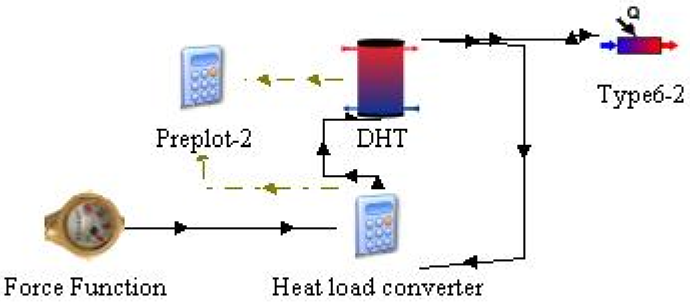


Figure 16 - DHT sub system

A global variable called *Etap_year*, located in the “Parameter settings” equation block, contains the annual energy consumption for tap water for each DHT. The “Parameter settings” is an equation block where most variables in the simulation are collected. This enables the user to change simulation parameters without having to click into every different type.

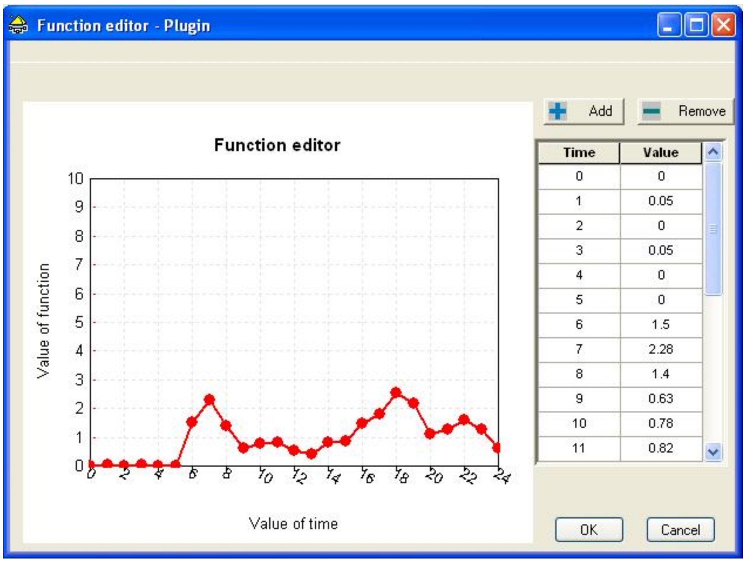
The *Etap_year* variable is calculated by using a typical yearly consumption for a household (3794 kWh) and multiplying it with the number of households per DHT. Initially the number of households per DHT is set to 1. By combining *Etap_year* with the desired set temperature for tap water (65 C), the average water consumption per hour is calculated using Formula 3.

Formula 3

$$Qavg\_hour = (Etap\_year / 8760) / Cp\_water \cdot (T\_tap - T\_source))$$

Qavg_hour:	Average tap water consumption per hour.
T_source:	Temperature of the water source, set to 10 degrees Celsius.
T_tap:	Set point temperature for the tap water.
Cp_water:	Heating capacity for water.

The daily variation in the tap water consumptions is modelled by the “Force Function” type. A measured profile from a Norwegian housing estate is used as a basis, and the function was normalized in order to make the daily average to 1. Figure 17 shows the profile as it is displayed in the simulation. Note that the load profile for each DHT is shifted with 15-30 minutes from each other to avoid identical water temperatures that could cause problems in the “Priority” controller.



Time	Value
0	0
1	0.05
2	0
3	0.05
4	0
5	0
6	1.5
7	2.28
8	1.4
9	0.63
10	0.78
11	0.82

Figure 17 - Tap water force function

The tap water force function is connected to the “Heat load converter” equation block. This block has two inputs, the instantaneous value of the “Force Function”, *Q_force,* and the outlet temperature of the DHT, *Tload_DHT*. These inputs are used in two equations. The first one, *Q_DHT,* calculates the needed outlet flow from the DHT in order to satisfy the tap water load. This function is shown in Formula 4.

Formula 4

$$Q\_DHT_n = (Qavg\_hour \cdot Q\_force_n) \cdot (T\_tap / \max(Tload\_DHT_n, T\_tap))$$

In short, the equation uses the average tap water demand and multiplies this with the hourly value to find the desired flow rate. If the tank outlet temperature is higher than the *T_tap* temperature, the flow rate is reduced accordingly.

The second function, *Pdemand*, simply calculates the hourly power flow and makes this available for plotting and integration.

"Preplot" is merely an equation block used to get the outputs ready for plotting and recording.

Storage tank and heater

The DHT type is a storage tank model with fixed inlets and an internal heating element. Because the object is designed for solar heating system it has two inlets and two outlets, allowing a separate reheating circuit, but only one inlet and one outlet will be used in this simulation. The tank itself is stratified, consisting of *n* (*n* < 15) fully mixed layers (nodes).

The tank's properties can be modified by changing a number of settings. The most important are:

Parameters

V_DHT	The tank's storage capacity
Tset_DHT	The set temperature
P_DHT	The rated power of the heating element
DB_DHT	Dead band of the thermostat
Nnode_DHT	Number of nodes (temperature levels) to be used

In addition, the model has the following inputs and outputs:

Inputs

Cold-side temperature	Temperature of the liquid flowing into the tank
Cold-side flow rate	Flow rate of the cold-side stream
Environment temperature	Temperature of the environment in which the tank is located
Control signal for element n	Control signal for the auxiliary heater

Outputs

Temperature to load	Temperature of the liquid flowing out of the tank
Flow rate to load	Flow rate of the load stream
Thermal losses	Rate of thermal energy loss to the environment
Auxiliary heating rate	Average rate of power flow to the tank by auxiliary heater
Average tank temperature	Average temperature of the liquid in the storage tank
Energy rate to load	Rate of energy removed from the tank to supply the load

During the simulation, the tank has two inputs that change over time. Those are:

Cold-side flow rate: This input is the *Q_DHT* variable calculated in the equation block "Heat load converter". Since the tank always has a finite amount of water, the cold side flow rate forces a similar flow rate to the load from the output *Flow rate to load*.

Control signal: This binary control signal is received from the "Thermal load controller", and decides if the tank will be on or off. Note that the tank will not switch on regardless of the control signal if the water temperature is higher than the set point temperature *Tset_DHT*, defined in "Parameter settings".

Reheating coil

Since the DHT tank temperature varies with the load demand and the available excess wind energy, the system needs a reheating coil to ensure the tap water temperature is high enough when utilized. This secondary heating element should hold the properties of a typical peak load heater; a high power output and a low installation cost. The operation cost is not as important, since the DHT system should ideally cover the bulk of the energy supplied.

For Nólsoy, the choice stands between either an electric or an oil fuelled re-heater. Electric heaters are cheap and desire little maintenance, but for this setup an oil fuelled heater was found to be most suitable. Firstly, all households on Nólsoy already have an oil tank, so the installation costs would be reduced compared to a full installation. Second, since the DHT is solely dependant on electricity, it would be wise to include a secondary energy carrier to ensure a security of supply should the electricity grid fail. This will also lower the maximum power demand for the stand-alone system, reducing the system cost.

Inputs for the reheating coil are the mass flow and temperature of the water leaving the DHT. The only output was the required heating rate, or more accurately the power needed to heat the fluid to the set point temperature.

Configuring the model

The wind and electric load series were not changed from the base case model, but because of the additional energy demand, the windmill was upgraded to an Enercon E-48 with a rated output of 800kW.

Additional plotters and integrators were added to the most interesting outputs from the electrical and thermal system.

The number of DHTs to be modelled was one of the key issues that had to be addressed. The ideal solution would be to create an equal amount of DHT subsystems to match the number of households on Nólsoy. However, this is not practically achievable with the TRNSYS software, since all connections and outputs have to be manually connected and configured. It was decided that a maximum of four individual DHTs were to be connected to the system at the same time. This would make it possible to monitor each subsystem individually, and at the same time investigate the system response to different operating and priority strategies.

Because the simulation only models a limited number of DHTs, the amount of excess wind power available to the thermal controller was scaled down to *Pdump*PdumpUnitRatio*nDHT,* where *PdumpUnitRatio* equals (1/*number of households*) and *nDHT* the number of DHTs modelled in the simulation. After the simulation was run, the outputs were scaled up accordingly so they represent the total energy system, and not just 4 units.

Figure 18 shows the complete Wind-Diesel-DHT model with all outputs connected. The solid black lines represent actual power flow.

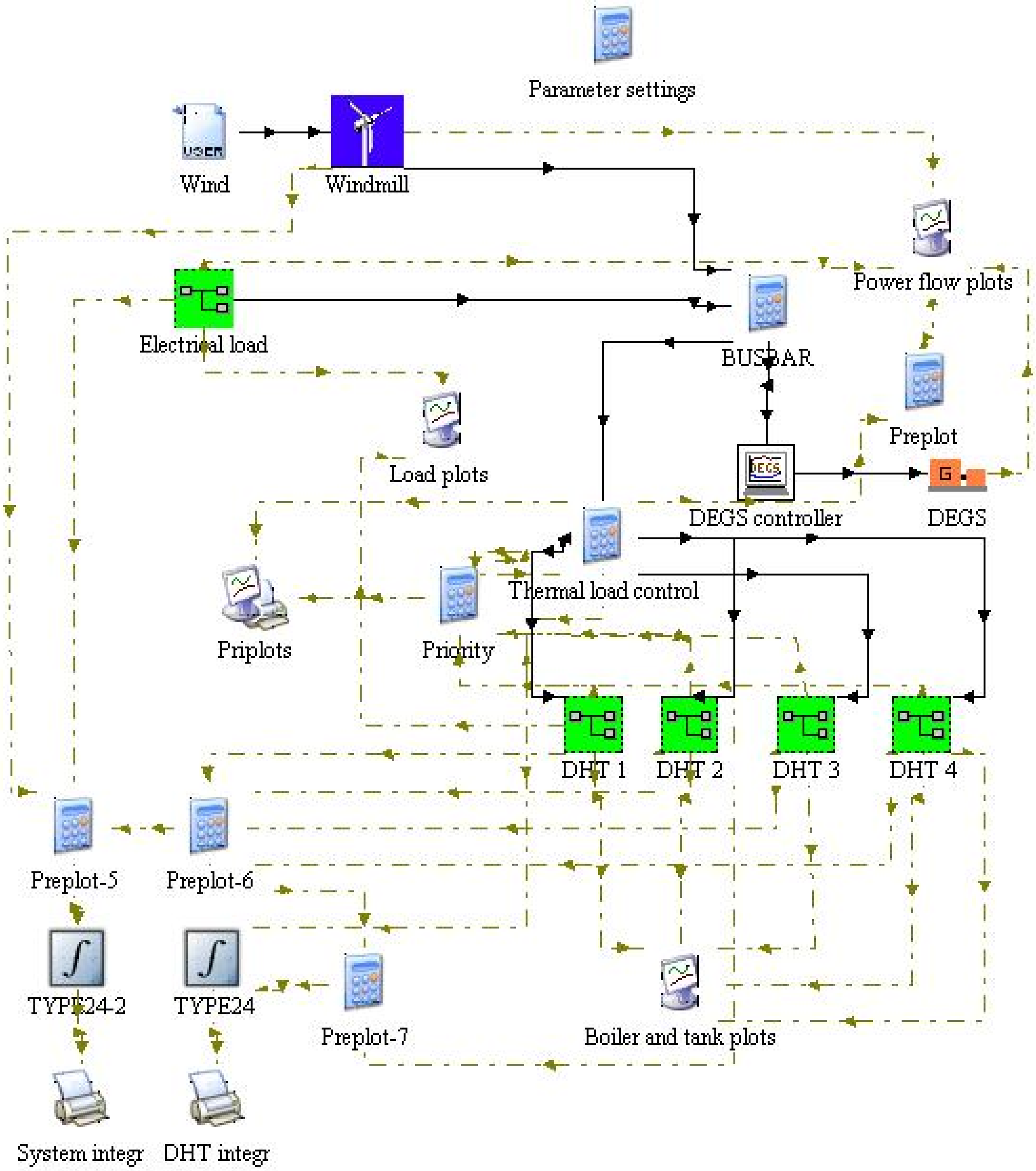


Figure 18 - TRNSYS model, scenario II

The complete list of system settings can be found in appendix I.

4.3.1 Simulation results

Reference system

As for scenario I, the simulation was run once with the DHT units turned off and all tap water demand served by the reheating coil. The environmental temperature *T_envi* was set equal to the temperature of the water source, *T_source* at 10 Celsius. This temperature is assumed to be the temperature of the room of which the tank is located, often a cold cellar on Nólsoy.

The initial temperature of the water in the DHT, *T_init*, was set equal *T_envi*. This was done to prevent that an initial storage of energy in the DHT would be delivered to the consumers.

The simulation results are shown in Table 8.

E_{LOAD} [MWh]	E_{WECS} [MWh]	E_{DEGS} [MWh]	E_{DEMTAP} [MWh]	E_{DELTAP} [MWh]	E_{AUXTAP} [MWh]	$E_{LOSSTANK}$ [MWh]	E_{REHEAT} [MWh]	Q_{FUEL} [litre]
1366	4218	489	386	0	0	0	386	161180

Table 8 - Simulation outputs scenario II - Reference system

Below is a brief description of the different variables in the table. All energy figures are in MWh.

E_{LOAD}:	Total electric load
E_{WECS}:	Electricity generated by the windmill
E_{DEGS}:	Electricity generated by the DEGS
E_{DEMTAP}:	Total tap water energy demand
E_{DELTAP}:	Energy delivered from DHT to the tap water load
E_{AUXTAP}:	Electricity consumed by the DHTs
$E_{LOSSTANK}$:	Thermal losses from the DHTs
E_{REHEAT}:	Energy consumed by the reheating coil
Q_{FUEL}:	Diesel consumption by the DEGS [litre]

Default settings

The simulation was run for one year with hourly values and the default settings, but this time with the DHTs enabled by setting the power of the heating elements to 2000 W for each individual DHT, and a tank size of 1 m^3. Table 9 shows an overview of the main outputs.

E_{LOAD} [MWh]	E_{WECS} [MWh]	E_{DEGS} [MWh]	E_{DEMTAP} [MWh]	E_{DELTAP} [MWh]	E_{AUXTAP} [MWh]	$E_{LOSSTANK}$ [MWh]	E_{REHEAT} [MWh]	Q_{FUEL} [litre]
1366	4281	489	386	309	595	201	81.9	161180

Table 9 - Simulation outputs scenario II - Default settings

A large share of the tap water demand was covered by using excess wind power in the DHTs, more exactly 80%. However, a very large share of the energy supplied to the DHT was lost as thermal loss (34%). These results could imply that the thermal model of the tap water tank was not properly configured. The storage tank was currently modelled with only one node, meaning the temperature of the whole tank was uniform. Considering the size of the tank (1 m^3), a stratification of temperature layers was likely to occur. An attempt was made to investigate the impact of this variable, by running a series of simulations with different number of nodes.

System design options

Number of temperature levels (nodes) in the DHTs

Table 10 shows an overview of the simulation results while varying the number of nodes. Several of the fixed results, like E_{LOAD}, E_{WECS} and E_{DEGS} have been removed from the output.

Parameters	**Results**					
N_{Node}	E_{DELTAP} [MWh]	$\%_{DELTAP}$	E_{AUXTAP} [MWh]	$E_{LOSSTAP}$ [MWh]	$\%_{LOSSTANK}$	E_{REHEAT} [MWh]
1	309	80%	595	201	34%	81.9
2	318	82%	484	107	22%	75.3
3	312	81%	442	83	19%	81.4
4	305	79%	415	70	17%	87.2
5	300	78%	395	62	16%	92.0
6	295	76%	381	56	15%	96.4
7	291	75%	369	52	14%	100
11	280	73%	340	43	13%	111
15	271	70%	319	38	12%	120

Table 10 - System outputs scenario II - Number of temperature nodes in the system

N_{Node}:	Number of nodes modelled
$\%_{DELTAP}$:	Percentage of tap water demand covered by the DHTs
$\%_{LOSSTAP}$:	Percentage of energy added to DHT lost as thermal loss

The number of nodes modelled had a considerable effect on the system performance. First of all, the $E_{LOSSTAP}$ variable fell considerably, as expected. The reason for this change is most likely the stratification of the tank temperature. Even when the relative level of energy stored in the tank is low, the temperature at the top outlet will still be high enough to deliver tap water, while the replacement water at the bottom holds a much lower temperature.

In total, the thermal loss from the storage tanks relative to the amount of energy added was reduced with 65% when raising the number of nodes from 1 to 15.

The rate of energy delivered from the DHT to the load fell with the adding of nodes, resulting in higher energy consumption in the reheating coil. This effect can be traced to the E_{AUXTAP} variable, the amount of electricity consumed by the DHT, which was reduced by over 46% when going from 1 to 15 nodes. The stratification of the tank temperature causes the water in the top of the tank, *Tset_DHT*, to reach the maximum allowable temperature (85 C) more often, forcing the heating element to shut down even though excess wind power is available. When comparing that the delivered energy *to* the DHT fell with 46%, but the delivered energy *from* the DHT only fell with 12%, the effects of a stratified storage tank model becomes more clear.

Figure 19 displays how the different variables change when the number of nodes is increased. As mentioned, the storage tank model is written to handle up to 15 different nodes. The question is if an even more detailed model would have a significant impact on the simulation results. As seen on the graph, the increase in nodes has a much greater impact when going from 1 to 2 nodes than going from 14 to 15. By visual inspection it would seem that the impact from adding even more nodes would not alter the outputs drastically. Any change would either way be insignificant compared to the error range in for example the energy consumption inputs or the wind series.

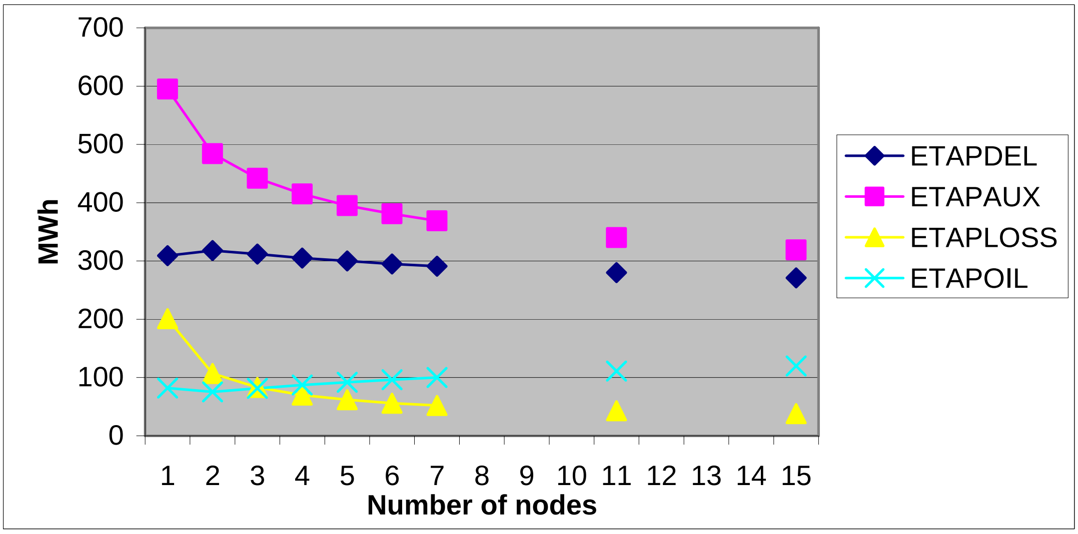


Figure 19 – System performance versus number of temperature nodes in the storage tank

Storage tank volume

One of the most important variables in the energy system is the storage tank size. Not only does it affect how the total system will perform, but the size, cost and properties of the tank system will greatly affect the feasibility of the scenario, since the different households will have the tank installed in their own homes. A tank of 3 m^3 might have a very good performance, but will most likely be too big to install in a normal household.

The geometrical shape of the tank affects its thermal properties, such as heat loss and stratification. Initially, the tank was modelled as a cylinder with a relationship between the height and the radius of two to one, meaning that the height was twice the radius independent of the tank size. This ratio will give the lowest possible surface area, reducing thermal losses, and the ratio will be used for the tank size sensitivity analysis.

The tank will be modelled with 15 thermal nodes for the greatest possible accuracy. Table 11 shows the most important outputs from the simulation.

Parameters	**Results**						
V_{DHT} [litre]	***r/h DHT***	E_{DELTAP} [MWh]	$\%_{DELTAP}$	E_{AUXTAP} [MWh]	$E_{LOSSTANK}$ [MWh]	E_{REHEAT} [MWh]	$\%_{REHEAT}$
150	*0.29/0.58*	*179*	*46%*	*187*	*8*	*210*	*54%*
250	0.34/0.68	199	52%	212	13	188	49%
500	0.43/0.86	245	63%	272	24	143	37%
750	0.49/0.98	258	67%	295	30	131	34%
1000	0.54/1.08	271	70%	320	38	120	31%
1250	0.59/1.17	277	72%	337	46	114	30%
1500	0.62/1.24	281	73%	352	53	110	28%
2000	0.68/1.37	287	74%	376	66	104	27%

3000	0.78/1.56	295	76%	419	89	96	25%

Table 11 - System outputs scenario II - Storage tank size

V_{DHT}: Tank size of DHT [litre]
r/h *DHT*: Radius and height of the DHT tank [m]
$\%_{REHEAT}$: Energy demand in the reheating coil as a percentage of the total tap water energy demand

Figure 20 displays how the oil consumption is reduced with the different tank sizes compared to a pure externally heated system. In general, the larger the tank the more oil can be saved, but the ratio falls when the tank size increases. At one point the process will be reversed as the thermal losses will grow too big, but it was chosen to limit the tank size to 3 m^3 since bigger sizes appeared as totally unrealistic.

As can be seen in Table 11, larger tank sizes yields more thermal loss and demands more excess energy from the grid. The ratio of loss versus gain grows bigger with increased tank size. For example, increasing the tank size from 1500 to 2000 litres reduces the oil consumption with 1%, but the electricity consumption increases with 7%.

Eventually the question boils down to if the extra oil savings can economically justify a larger tank investment, and if the extra excess power has an alternative cost, meaning if it can be utilized in other parts of the energy system. This will be discussed later in the thesis.

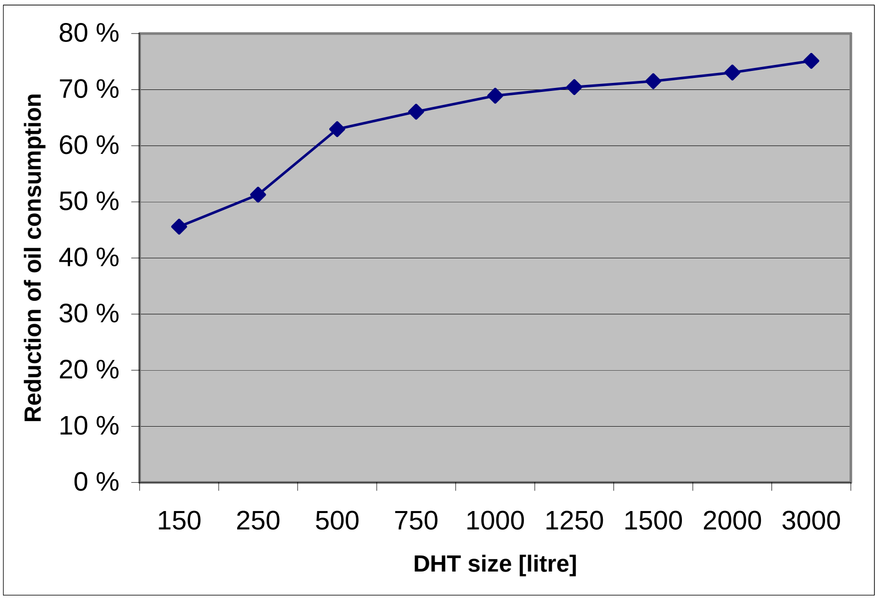


Figure 20 - Oil consumption versus DHT tank size

Maximum heating rate of DHT

Another crucial variable in the DHT sub system is the maximum heating rate of the DHTs. The reason for this variable's importance is the way the excess energy is divided to the heaters. Let's say there is excess wind power of 10 kW available for the four DHTs. If the rated power of each DHT is 2kW (default setting), then all four heaters would be switched on, but 2 kW would go to waste. If the rated power on the other hand was 3kW, then three heaters would operate, and 1kW would go to waste. In short, low rated power of the DHTs will ensure that they are switched on often, but lots of energy would go to waste if the power available is high. On the other hand, a large rated power would mean that a lot of energy could be utilized when the excess power was high, but at low power surplus you might not be able to turn on any of the heaters at all.

Table 12 shows the results of a simulation where the rated power of the DHTs, the *P_DHT* variable, is varied.

Parameters	**Results**					
P_{DHT} [W]	E_{DELTAP} [MWh]	$\%_{DELTAP}$	E_{AUXTAP} [MWh]	$E_{LOSSTANK}$ [MWh]	E_{REHEAT} [MWh]	$\%_{REHEAT}$
500	257	67%	305	35	132	34%
750	286	74%	343	43	107	28%
1000	290	75%	348	44	104	27%
1250	288	75%	345	44	106	27%
1500	285	74%	340	43	109	28%
2000	271	70%	320	38	120	31%
2500	252	65%	298	36	137	35%
3000	240	62%	283	34	148	38%
4000	213	55%	251	31	178	46%
5000	185	48%	218	27	204	53%

Table 12 - System outputs scenario II – Maximum heating rate of DHT

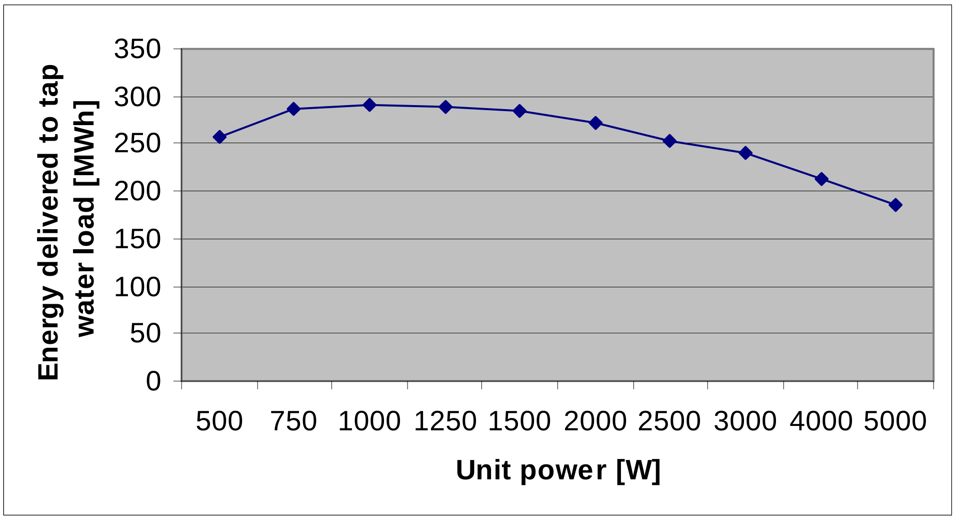


Figure 21 - Energy delivered to tap water versus maximum unit power of DHT

Figure 21 shows that the maximum energy utilization occurs when the heating element is around 1000 W. However, the amount of energy utilized changes only with one percent when the element size is varied from 750 to 1500 W, making it hard to conclude on an “optimal” element power. Most likely other system settings will affect this ratio, such as the tank size. It seems clear however that elements bigger than 1500 W will decrease the system performance at the current settings.

Temperature settings

There are mainly two temperature settings that can be controlled and that could affect the system performance, the tank set point temperature *Tset_DHT*, and the dead band temperature *DB_DHT*.

The tank set point temperature describes the maximum allowable tank temperature. A high set point temperature means that more energy can be stored in the tank, but will also increase the thermal losses. To avoid the possibility of boiling, this temperature cannot be set higher than 95 degrees Celsius, and since the tap water demand is at 65 C, this will be the minimum limit. The default Tset_DHT is 85 C.

The dead band temperature describes how far the tank temperature will fall below the *Tset_DHT* temperature before the heating element is turned on again (given a positive control signal), and the main reason it's being utilized is to prevent a rapid rate of switching of the heat element. The default dead band is 5 C.

The simulation was run with a tank size of 1000 litres and a 1000 W heating element. The outputs can be seen in Table 13.

Parameters		**Results**					
T_{SET_DHT} [C]	T_{DB_DHT}	E_{DELTAP} [MWh]	$\%_{DELTAP}$	E_{AUXTAP} [MWh]	$E_{LOSSTANK}$ [MWh]	E_{REHEAT} [MWh]	$\%_{REHEAT}$
95	*2.5*	298	77%	364	50	100	26%
	5	298	77%	363	50	100	26%
	7.5	297	77%	362	49	101	26%
90	5	294	76%	356	47	102	26%
85	2.5	291	75%	349	45	104	27%
	5	290	75%	348	44	104	27%
	7.5	289	75%	347	44	105	27%
80	5	286	74%	340	42	107	28%
75	2.5	282	73%	333	39	109	28%
	5	281	73%	331	39	110	28%
	7.5	279	72%	328	38	110	28%
70	5	275	71%	321	36	113	29%
65	2.5	269	70%	312	34	118	31%
	5	266	70%	308	33	120	31%
	7.5	260	67%	301	33	126	33%

Table 13 - Simulation outputs scenario II - DHT tank temperature and dead band

The dead band temperature was changed between three different levels, 2.5, 5 and 7.5 degrees. Because of the large number of simulations, only half of the different set temperatures were simulated with a varying dead band.

The simulation results showed that the temperature level and dead band had a relatively small impact on the amount of energy delivered to the load. With a dead band of 5 C, the change in delivered energy was only 7% when reducing the tank temperature from 95 to 65 degrees Celsius. Adjusting the dead band while holding the set temperature constant resulted in a change in the delivered energy by less than two percent for all set temperatures, except 65 C.

All in all the set temperature and the dead band temperature had little effect on the amount of energy delivered, with the highest set temperature and the lowest dead band being the most favourable from an energy exploitation ratio point of view. With a simulation time of one hour, the effect of rapid power switching of the element due to the dead band temperature can not be investigated.

As a conclusion, technical issues such as the storage tank's recommended temperature level and dead band should be deciding when setting the tank parameters.

Summary

Varying the tank size had a noticeably effect on the system performance, and a bigger tank gave a higher energy yield. However, the ratio of useful energy to added energy fell with the increase in tank size as the thermal losses rose, and the investment cost will also be higher with a bigger tank. 1000 litres was found to be a suitable size with high energy utilization but reduced thermal losses.

Unlike the tank size, the maximum heating rate of the DHT had a defined optimal interval from 750 to 1500 W. The performance difference within this interval was minimal, so 1000 W was chosen as a basis.

Changing the tank temperature had small effects on the system, but in general the higher temperature will give a better performance. The set point was chosen to 85 C to avoid any raised investment cost related to a very high tank temperature.

4.4 Scenario III: Wind-Diesel-DHT: Space heating

The introduction of a DHT subsystem to utilize excess wind power for tap water heating showed promising simulation results. At best, over 75% of the tap water demand was covered, corresponding to a decrease in oil consumption of almost 300 MWh. The amount of utilized wind power with the 800 kW turbine was raised from about 900 MWh (21%) to 1200 MWh (27%). However, the greater part of the wind energy still remains unused. Considering the electricity and tap water load on Nólsoy only corresponds to about 27% of the total energy consumption, there exists a great potential for utilizing more wind power as a substitute for fossil fuel.

Most of the remaining energy consumption is oil-based space heating in the households. The idea of scenario 3 is in many ways similar to scenario 2; using distributed domestic heating tanks that utilize excess wind power, but this time to cover the space heating load, which is roughly 7-8 times as large as the tap water load.

The energy consumption for space heating per household was estimated to 28125 kWh per year. Multiplying by the number of households, this sums up to 2.9 GWh.

The simulation setup is in general equal to the tap water setup in scenario II. The excess wind power is distributed to DHTs where it is converted into thermal energy and stored. Hot water is drawn from the top of the tank to cover the heating demand, and is reheated in a separate reheating coil should the temperature be below the desired temperature in the radiators, *T_radiator*. The major difference from the tap water setup is that the heated water returns to the DHT after giving off heat in the radiators. This required a redesign of the DHT subsystem.

DHT subsystem

Figure 22 shows a picture of the redesigned DHT subsystem.

Heating load

The thermal controller was completely redone. In contrary to the tap water load, that is assumed to have a constant profile throughout the year, the heating demand fluctuates due to the seasonal temperature change. A week load profile similar to the electric load was combined with the daily load ratio to form a complete yearly profile of hourly values. To cover the heat demand, the load controller used the water temperature from the reheating coil as an input, and with the help of the specific hourly power demand calculated the output temperature from the load, which was directed back to the DHT. The water flow rate was defined as a constant value, chosen high enough to prevent the output temperature from the thermal load to fall below room temperature; else the heat energy could not be transferred to the load. The calculated power demand (Formula 5) and the actual power flow (Formula 6) were directed as outputs to enable an energy balance check.

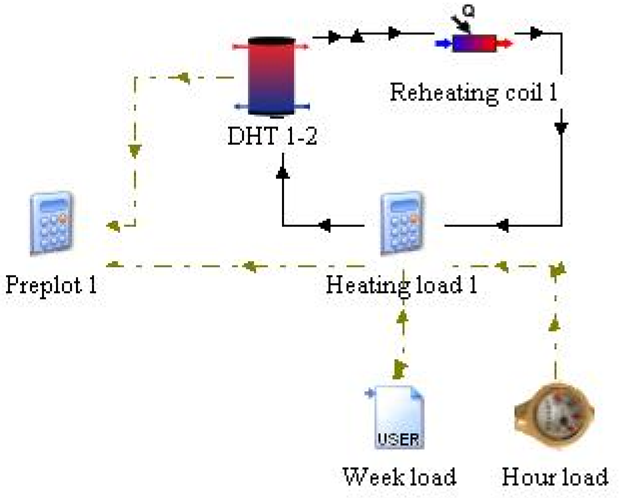


Figure 22 - DHT sub system

Formula 5

Desired power demand:

$$P_{demand} = WeekLoad \cdot HourLoad \cdot Pavg\_hour$$

Actual power delivered:

$$P_{delivered} = Q_{radiator} \cdot Cp_{water} \cdot (Tin_{radiator} - Tout_{radiator})$$

Formula 6

WeekLoad:	Relative load of the week
HourLoad:	Relative load of the hour
Pavg_hour:	Average heat load over the year
$Q_{radiator}$:	Water flow in the load circuit
$Tin_{radiator}$:	Temperature in to the load unit
$Tout_{radiator}$:	Temperature out of the load unit

4.4.1 Simulation results

Reference system

For the reference system, the DHT heating elements were switched off in order to get a reference value for oil consumption. The simulation results can be seen in Table 14, all results in MWh if something else is not specified. For a complete list of settings, see appendix I.

E_{LOAD} [MWh]	E_{WECS} [MWh]	E_{DEGS} [MWh]	$E_{DEMHEAT}$ [MWh]	$E_{DELHEAT}$ [MWh]	$E_{AUXHEAT}$ [MWh]	$E_{LOSSTANK}$ [MWh]	E_{REHEAT} [MWh]	Q_{FUEL} [litre]
1366	4281	489	2882	-116	0	166	3000	161180

Table 14 - Simulation outputs scenario III - Reference system

$E_{DEMHEAT}$: Total heating demand, households
$E_{DELHEAT}$: Energy from the DHT delivered to the heat load
$E_{AUXHEAT}$: Electricity consumed by the DHTs
$E_{LOSSTANK}$: Thermal losses from the DHTs
E_{REHEAT}: Energy consumed by the reheating coil
Q_{FUEL}: Diesel consumption by the DEGS [litre]

The windmill and electricity load settings were not changed from scenario II, meaning the E_{LOAD}, E_{WECS}, E_{DEGS} and Q_{FUEL} variables remain unchanged. $E_{DEMHEAT}$, the total space heating demand, corresponds to an average consumption of 28125 KWh per households. $E_{DELHEAT}$, defined as the difference in the energy of the water flowing out of the tank from the water flowing into the tank, is lower than the thermal losses because of the difference in the energy storage level in the tank from the start to the end of the year.

The thermal losses from the storage tank have grown substantial, mainly because of the high average temperature in the tank. Since the water from the radiators is returned to the tank at the bottom node, and the flow rate is rather high compared to the tap water scenario, the stratification effect is much less dominant resulting in increased thermal losses. It must be taken into account that the energy flow through the system is much higher than in scenario II, and hence the losses increase accordingly.

E_{REHEAT} is the energy amount added in the reheating coil to satisfy the thermal load, and equals the heating demand variable plus the difference in the tank's energy storage level.

Default settings

The heating elements were then activated and a simulation was run with the same parameter settings as the reference case, with a tank volume of 1000 litre and heating element of 1000 W. The results are displayed in Table 15:

E_{LOAD} [MWh]	E_{WECS} [MWh]	E_{DEGS} [MWh]	$E_{DEMHEAT}$ [MWh]	$E_{DELHEAT}$ [MWh]	$E_{AUXHEAT}$ [MWh]	$E_{LOSSTANK}$ [MWh]	E_{REHEAT} [MWh]	Q_{FUEL} [litre]
1366	4281	489	2882	398	550	168	2484	161180

Table 15 - Simulation outputs scenario III - Default settings

A total of 398 MWh of energy was added to the DHTs and utilized in the load. This is approximately 100 MWh more than the best tap water scenario, but with a utilization rate of the wind energy of 30%, the potential for improvement is still great.

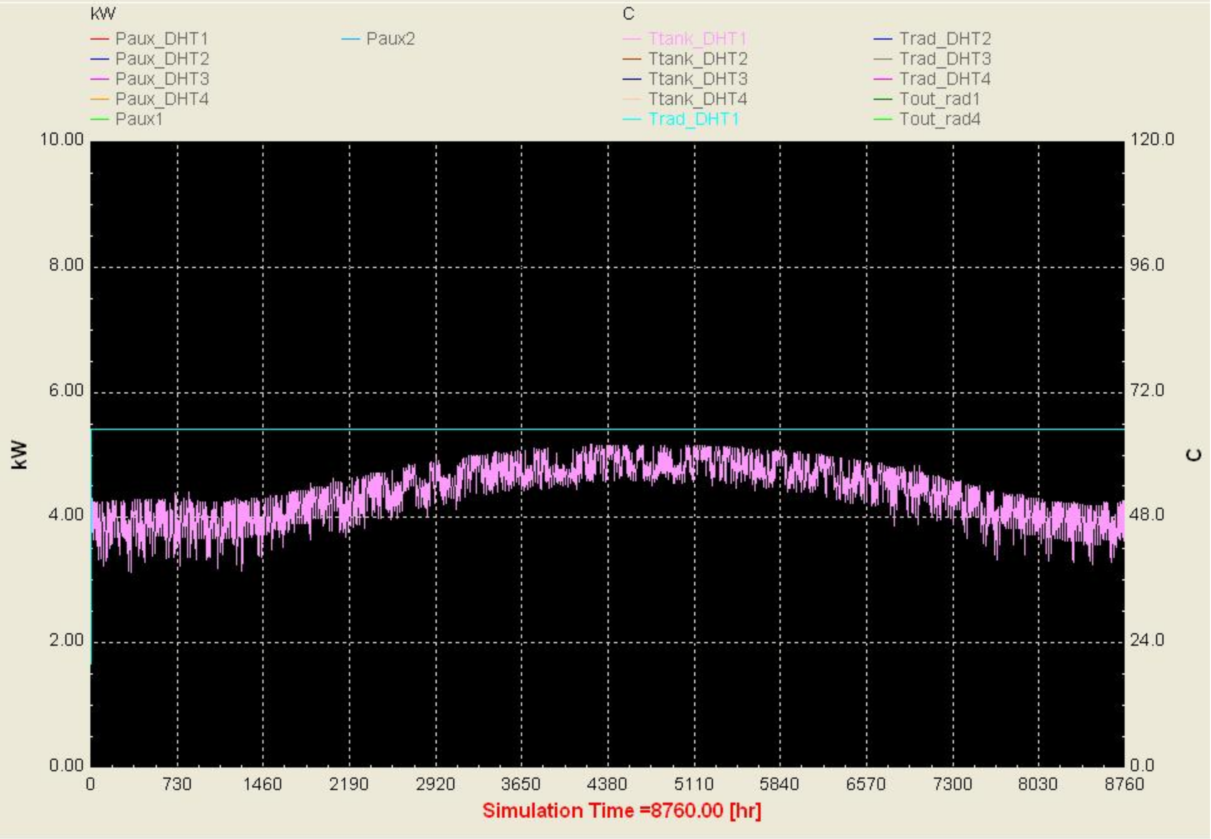


Figure 23 - Simulation plot, scenario III

Figure 23 shows a plot from the simulation. The turquoise graph displays the temperature of the water entering the radiator, while the pink graph displays the temperature of the top node of the storage tank. As the graph shows, the tank temperature is never in the range of the upper set point temperature of 85 C, so no available energy is rejected from the DHT due to full storage capacity (which frequently happened in the tap water simulations).

In order to improve the wind energy utilization rate, a number of simulations were run while varying key variables.

System design options

Storage tank volume

Since the energy storage level never was completely utilized during the initial simulation, a change of the tank size could possibly reduce the thermal losses and improve the system performance. A number of simulations were run while varying the storage tank size. The simulations are summarized in Table 16.

Parameters	**Results**						
V_{DHT} [litre]	***r/h DHT***	$E_{DELHEAT}$ [MWh]	$\%_{DELHEAT}$	$E_{AUXHEAT}$ [MWh]	$E_{LOSSTANK}$ [MWh]	E_{REHEAT} [MWh]	$\%_{REHEAT}$
50	0.20/0.40	532	18%	550	23	2351	78%
100	0.25/0.50	522	18%	550	37	2360	79%

150	0.29/0.58	514	18%	550	48	2369	79%
250	0.34/0.68	498	17%	550	68	2385	80%
500	0.43/0.86	463	16%	550	107	2420	81%
750	0.49/0.98	429	15%	550	139	2453	82%
1000	0.54/1.08	398	14%	550	168	2484	83%
1250	0.59/1.17	369	13%	550	194	2513	84%
1500	0.62/1.24	341	12%	550	219	2541	85%
2000	0.68/1.37	291	10%	550	264	2592	86%
3000	0.78/1.56	203	7%	550	343	2679	89%

Table 16 - Simulation outputs scenario III - DHT tank volume

The system was simulated with storage sizes down to 50 litres.

In contrary to the tap water scenario where the amount of utilized energy increased with an increase in tank size, the opposite was the case for scenario III. The reason can be seen from the $E_{AUXHEAT}$ variable, which remained constant throughout the simulation. This confirms the assumption that the storage level is oversized, or seen from a different view, the excess energy added is too low. Even with storage tank of only 50 litres the added excess wind power could never bring the tank temperature above 65 C, far below the set temperature of 85 C.

Maximum heating rate of DHT

In scenario II, the storage tank had trouble absorbing the excess wind power in periods with high wind, because the thermal storage capacity was full. The solution that yielded the best energy utilization ratio was to reduce the element power in order to increase the operating time.

For the space heating case in scenario III, the problem is reversed. All excess wind energy is added to the heaters, but the goal is to raise the available power. This will be attempted by increasing the rated power of the heating elements at the sacrifice of operating time.

The simulation was initialized with a storage tank of 500 litres.

Parameters	**Results**					
P_{DHT} [W]	$E_{DELHEAT}$ [MWh]	$\%_{DELHEAT}$	$E_{AUXHEAT}$ [MWh]	$E_{LOSSTANK}$ [MWh]	E_{REHEAT} [MWh]	$\%_{REHEAT}$
500	217	8%	307	106	2666	89%
750	346	12%	434	107	2537	85%
1000	463	16%	550	107	2420	81%
1250	564	20%	649	107	2319	77%
1500	641	22%	724	107	2241	75%
1750	611	21%	689	107	2273	76%
2000	629	22%	703	107	2256	75%

2500	543	19%	609	107	2351	78%
3000	595	21%	660	107	2317	77%
4000	425	15%	480	107	2509	84%
5000	484	17%	539	107	2487	83%
6000	482	17%	536	107	2527	84%

Table 17 - Simulation outputs scenario III - Maximum heating rate of DHT

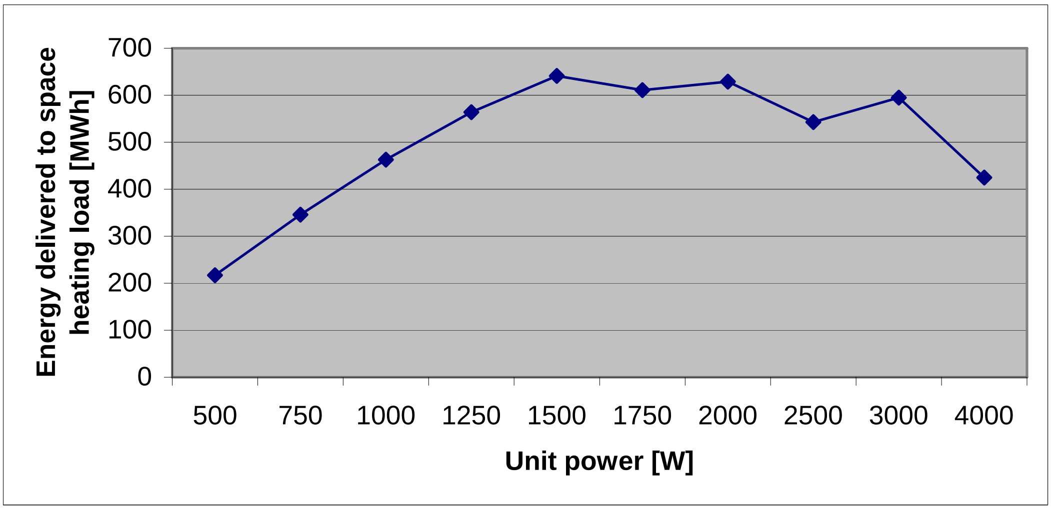


Figure 24 - Energy delivered to space heating load versus DHT unit power

Figure 24 shows a plot of the energy delivered to the space heating load with different unit power sizes. The utilization rate rose nearly linear from 500 up to 1500 W, where the peak was reached at 641 MWh, 22% of the heating demand. From 1500 to 3000 W the power output was fluctuating, but still at a high level. The energy variation in this interval was most likely a result of random match between the excess wind power and the unit power, and with another wind profile from the same site but another year, the results might have been different.

If a choice had to be made between two different unit powers with nearly the same energy yield, for instance 1500 and 2000 W, the smaller one would most likely be better from an operational point of view. A smaller rated power would mean a longer operating time and lower power spikes when switching, improving grid stability and quality.

A few additional simulations were run to study the system behaviour with a heating element of 1500 W with varying storage tank size. As Table 18 shows, the storage capacity was not reached and hence the lowest storage size gave the best energy yield.

Parameters		Results					
P_{DHT} [W]	V_{DHT} [litre]	$E_{DELHEAT}$ [MWh]	$\%_{DELHEAT}$	$E_{AUXHEAT}$ [MWh]	$E_{LOSSTANK}$ [MWh]	E_{REHEAT} [MWh]	$\%_{REHEAT}$
1500	50	708	25%	724	23	2176	73%
1500	100	699	24%	724	37	2184	73%
1500	150	691	24%	724	49	2192	73%
1500	250	677	23%	724	68	2207	74%

Table 18 - System outputs scenario III - DHT power and tank volume

Temperature settings

For scenario III the choice was made to not run any simulation with varying temperature settings. The reason for this was that the thermal storage capacity was never reached, in other words there would be no reason to increase the set point temperature since the current boundary was not limiting.

Summary

In contrary to the tap water scenario, where the rate of utilized energy rose with increased tank size, the opposite is the case for the space heating setup. The reason for this is the high power demand, meaning that all energy added to the system will be consumed by the load. Adding storage will only increase the thermal losses, and hence decrease system performance.

In conformity with scenario II, the heating element size had an optimal interval, but for scenario II this range was from approximately 1500 to 3000 W. 1500 W was chosen as the favourable setting, not only because it gave the highest energy output, but because a lower element size will give a longer working time and smaller load spikes, improving grid stability.

4.5 Load control strategy

The purpose of this section is to examine how control strategies for the excess wind power will affect the energy yield and system behaviour in general.

For all simulations performed in the previous chapters, the load priority was simple; the DHT with the lowest tank temperature was first in line to receive any excess power, the second lowest was number two in line, and so on. This control strategy assumes a two way communication, no time delay and perfect temperature readings from the tank.

The biggest drawback with this control strategy is the requirement of a two-way communication utility. This is achievable in practice for most cases, but will demand additional hardware, increasing investment costs. In some cases, it might not even be technically possible to utilize a two-way system. It would therefore be interesting to investigate the performance of a one-way control system.

The tank parameters used in each scenario are as follows:

Scenario II: *Tset_DHT* = 85 C, *P_DHT* = 1000 W, *V_DHT* = 1 m^3

Scenario III: *Tset_DHT* = 85 C, *P_DHT* = 1500 W, *V_DHT* = 0.05 m^3

4.5.1 Priority level control

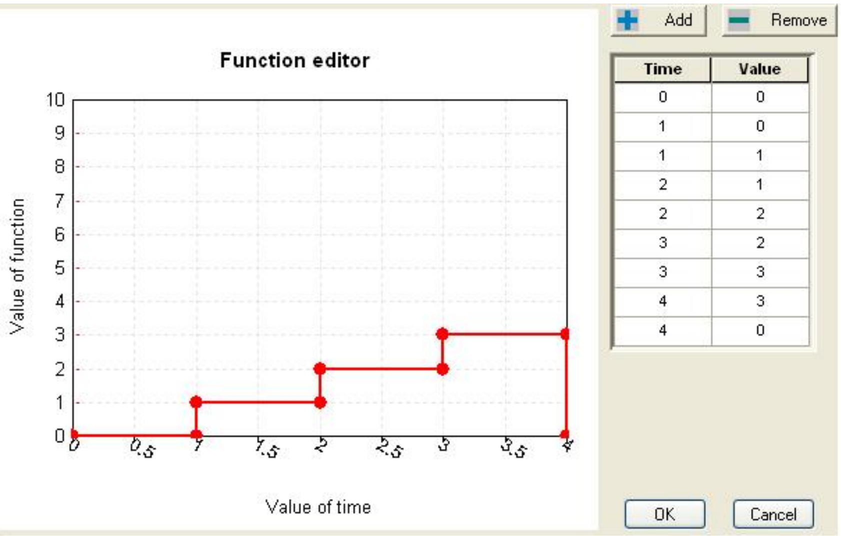
The key goal for the control system will be to spread out the excess wind power as equally as possible between the DHTs. In order to achieve this it is necessary to develop a priority system that decides what units are highest on the list to receive power when it becomes available, and to shift this priority at a given time interval.

The priority level is shifted by the load controller, and must be transmitted with the control signal. Each DHT must be able to interpret and identify its own, unique priority level.

Since the TRNSYS model only consists of four independent sub-systems, each of them are assumed to consist of one fourth of the total amounts of DHTs, and share the same priority level. This means that there will be four different priority levels.

The first rounds of simulations were run with a priority shift ever hour, every three hours and lastly every six hours. One hour was the lowest possible setting considering the simulation time.

Figure 25 shows the one-hour priority function for the first of the four DHTs. The average value of each hour defines the priority, and the function is looped every four hours. DHT nr 2 starts at a level of 1 at time 0, DHT 3 starts at 2 and DHT 4 starts at 3.



Time	Value
0	0
1	0
1	1
2	1
2	2
3	2
3	3
4	3
4	0

Figure 25 - DHT priority force function

System results

Scenario II:

Control settings	*EDELTAP* [MWh]	*%DELTAP*	*EAUXTAP* [MWh]	*ELOSSTANK* [MWh]	*EREHEAT* [MWh]	*%REHEAT*
Temperature control	290	75%	348	44	104	27%
One hour priority shift	290	75%	349	44	104	27%
Three hour priority shift	290	75%	347	44	105	27%
Six hour priority shift	289	75%	347	44	106	27%

Table 19 - System outputs load control strategy - Scenario II

Scenario III:

Control settings	$E_{DELHEAT}$ [MWh]	$\%_{DELHEAT}$	$E_{AUXHEAT}$ [MWh]	$E_{LOSSTANK}$ [MWh]	E_{REHEAT} [MWh]	$\%_{REHEAT}$
Temperature control	708	25%	724	23	2176	73%
One hour priority shift	708	25%	724	23	2176	73%
Three hour priority shift	708	25%	724	23	2176	73%
Six hour priority shift	708	25%	724	24	2177	73%

Table 20 - System outputs load control strategy - Scenario III

As Table 19 and Table 20 shows, the change in priority control had close to negible effect on the total system performance for all three time shift settings. This was the case for both the tap water and the heating load simulations.

Scenario II and scenario III are similar in setup, but the systems operate very differently. Scenario II, the tap water load, has a large renewable energy penetration (~75%) and relies on a large storage capacity in order to utilize the excess wind power. Scenario III on the other hand, with a space heating load, has a high power demand and a relatively low share of renewable energy (~25%). Since the energy added to the system can be utilized almost instantly all year around, there is no need for large energy storage.

The reason scenario II responds so well to the change in priority time, in addition to the storage capacity, is the low heating element power. When the heating element is operating uninterrupted, it takes almost 12 hours to raise the tank temperature by 10 degrees Celsius, even when there is no energy flow to the load. With an average tap water load drawn from the tank at the same time, the time of heating the tank 10 C is raised to over 20 hours. Similarly it takes 27 hours to lower the temperature by ten degrees with an average tap water load drawn from the tank, without considering thermal losses.

For scenario III, the heating demand alone is enough to absorb the energy added by the DHTs heating element. The average heating demand throughout the year is 3.2 kW, and in the warmest summer month the daily average is 1.7 kW. Compared to the maximum power of the heating element, which is set to 1.5 kW, this means that the excess power will never “go to waste” no matter the priority control, as long as the correct amount of DHTs are given a positive control signal.

DHT behaviour

All the simulations above were run with a nearly identical load profile in all DHTs. It would be interesting to examine how a difference in the load demand would affect the system behaviour, but most importantly the individual DHTs.

Because of the robust system response of the space heating system, these simulations will only be performed for scenario II, the tap water load, and only with 3 and 6 hour priority shifts.

To adjust the load demand, the “Force Function” type in each DHT was adjusted individually. The load profile of the first and the last DHT was lowered and raised with 20% respectively, while DHT 2 and 3 were adjusted by 10% in an identical fashion. In order to monitor each DHT more closely, the energy demand and energy delivery of each unit were connected to an integrator unit.

	E_{DEMTAP} [MWh]	$\%_{DEMTAP}$	E_{DELTAP} [MWh]	$\%_{DELTAP}$	$E_{AUXHEAT}$ [MWh]	E_{REHEAT} [MWh]
DHT1	76.4	19.8%	58.5	20.2%	73.1	19.5
DHT2	86.9	22.5%	65.5	22.6%	80.1	23.4
DHT3	107.0	27.7%	79.9	27.6%	94.3	29.2
DHT4	116.4	30.1%	85.9	29.6%	100.2	32.7
Total	386.7	100.1%	289.8	74.9%	347.7	104.8

Table 21 - System outputs differated loads - Temperature priority

	E_{DEMTAP} [MWh]	$\%_{DEMTAP}$	E_{DELTAP} [MWh]	$\%_{DELTAP}$	$E_{AUXHEAT}$ [MWh]	E_{REHEAT} [MWh]
DHT1	76.4	19.8%	59.2	20.5%	74.2	19.0
DHT2	86.9	22.5%	66.5	23.1%	81.4	22.5
DHT3	107.0	27.7%	78.7	27.3%	92.5	30.5
DHT4	116.4	30.1%	83.9	29.1%	97.5	34.7
Total	386.7	100.1%	288.3	100%	345.6	106.7

Table 22 - System outputs differated loads – 3 hour priority shift

	E_{DEMTAP} [MWh]	$\%_{DEMTAP}$	E_{DELTAP} [MWh]	$\%_{DELTAP}$	$E_{AUXHEAT}$ [MWh]	E_{REHEAT} [MWh]
DHT1	76.4	19.8%	59.9	20.8%	75.4	18.3
DHT2	86.9	22.5%	67.1	23.4%	81.4	21.9
DHT3	107.0	27.7%	77.3	26.9%	91.1	31.9
DHT4	116.4	30.1%	83.0	28.9%	97.0	35.6
Total	386.7	100.1%	287.3	100%	344.9	107.7

Table 23 - System outputs differated loads – 6 hour priority shift

As Table 21, Table 22 and Table 23 shows, the effect of adjusting the load balance had an insignificant impact on the system. Even with a 6 hour priority shift, the DHTs had almost the same E_{DELTAP}, the amount of useful energy delivered, as for the temperature controlled case.

The main reasons for these results are most likely that the tank storage capacity had been limiting the energy absorption at these settings. When the unit's consumption was increased, so was its ability to receive power. If the storage size had not been limiting, then all DHTs would in theory receive an equal amount of energy (depending on the wind), and the ones with the highest energy consumption would have had a poor utilization rate of renewable energy.

4.6 System Performance

A summary of all the three simulation scenarios is listed in table. For scenario II and III, the parameters have been chosen to return the highest possible energy yield. One exception from this is the *Tset_DHT* temperature of scenario that was set to 85 C instead of 95 C. The reason for this is the small difference in energy output (2.7%), and the uncertainty about all DHTs ability to run continuously at such high set temperature. For energy conversion between kWh and litres of diesel, an efficiency of 90% is used.

Scenario I: P_{WECS} = 300 kW

Scenario II: P_{WECS} = 800 kW, *Tset_DHT* = 85 C, *P_DHT* = 1000 W, *V_DHT* = 1 m^3

Scenario III: P_{WECS} = 800 kW, *Tset_DHT* = 85 C, *P_DHT* = 1500 W, *V_DHT* = 0.05 m^3

System	***Priority control***	***Average penetration [%]***	***Electric load served by wind [%]***	***Diesel savings inc. thermal [%]***	***Heating/tap water load served by wind [%]***	***Useful wind energy [% of total wind]***
Scenario I	-	113	57	55	-	50
Scenario II	One hour shift	313	64	63	75	29
Scenario III	One hour shift	313	64	25	25	37

Average penetration: The generated wind power compared to the total electric load.
Electric load served by wind: The share of the electric load covered by wind power.
Diesel savings inc. thermal: The total diesel savings for the scenario.
Heating/tap water load served by wind: The share of tap water (sc II) or heating (sc III) load covered by the wind power.
Useful wind energy: Share of the generated wind power utilized in the system.

4.7 Cost of Energy

The economic analysis in this section will not be a complete investment analysis. Configuring a complex economical model requires a lot of work, especially collecting the cost parameters. Local conditions can have great impact on costs, for instance related to the installation of the windmill, the requirement for grid investments and the transport cost of components. Few components can be used “off the shelf”, but have to be adjusted and possibly tailor made for each location.

Instead, an attempt will be made to compare the different scenarios to a pure Wind-Diesel setup. The extra energy yield that can be obtained from a DHT system will be compared to the required investment cost for the necessary additional system components, such as the DHT units and the control and communications system. The goal is to find the COE of the utilized thermal energy that would otherwise go to waste.

4.7.1 Energy savings

When calculating the energy savings, the scenarios are compared to a reference system where the electric load is covered by diesel generators and tap water/space heating load by fuel oil combustion (at 90% efficiency).

Scenario I: Wind-Diesel

Reference system:	Diesel: 421780 litres
Scenario I:	Diesel: 189395 litres
Savings:	Diesel: 232385 litres

Scenario II: Wind-Diesel-DHT (tap water)

Reference system:	Diesel: 421780 litres	Fuel Oil: 42464 litres
Scenario II:	Diesel: 161180 litres	Fuel Oil: 11441 litres
Savings:	Diesel: 260600 litres	Fuel Oil: 31023 litres

Scenario III: Wind-Diesel-DHT (space heating)

Reference system:	Diesel: 421780 litres	Fuel Oil: 317052 litres
Scenario III:	Diesel: 161180 litres	Fuel Oil: 239384 litres
Savings:	Diesel: 260600 litres	Fuel Oil: 77668 litres

4.7.2 Energy cost

The energy costs are gathered from Faroese companies in June 2006.

Electricity: The electricity price on the Faroe Islands is general for all consumers, but scales with the consumption. For consumption between 0-10000 kWh per year, which applies for the large majority of the Faroese households, the price is 1.11 DKR/kWh, corresponding to 0.15 €/kWh (SEV 2006).
Diesel: The only available diesel price was the price per litre delivered from a service station. There will most likely be discounts with larger purchases, but since the rate was unknown, the price was reduced from 6.83 DKR/litre to 5.00 DKR/litre (0.682 €/litre).
Fuel oil: The fuel oil price, derived from the price per 1000 litres and delivered from a tanker, is 5.813 DKR/litre, corresponding to 0.793 €/litre (Shell 2006).

4.7.3 Investment cost

It will be assumed that the only components needed to expand a wind-diesel system to a wind-diesel-DHT system are (1) the DHTs, (2) the communication carriers, (3) the central load commander and (4) the distributed load controller. Estimating the cost of these components can be complicated, because these systems are not widely commercially available. The best source was found to be (Johnson et al, 2002), where the cost of the communication hardware alone was estimated to approximately $1200 (938 €) per load control unit, the control hardware to 50% of the total cost of the heating system, and the thermal storage units to $800 - $1500 (626-1173 €) per household. The compared storage units are not DHTs but ETSs (electric thermal units), but the DHT price is assumed to lie in the same range.

Scenario III was found to perform better and better with a decreased storage size. It might even be possible to skip the DHT altogether and install an electric heating element directly in the already existing heating unit. This will further decrease investment cost. However, for the economic analysis performed in this chapter, both scenarios II and III will include a DHT unit.

The cost of the control hardware was claimed to be 50% of the total cost of the heating system for a 16 unit system (Johnson et al, 2002). For the Nólsoy case, with over 100 units, this percentage will most likely be lower. Both because there are more units to spread the cost on, but also because the price of integrated circuits, controllers and communication equipment have been steadily decreasing. For the economic analysis, the cost will be reduced to 25% of the total heating system cost.

The total investment costs per household will be set to 2640 € with a lifetime of 20 years, and is assumed to be on the high end of the cost estimate range. The interest rate is set to 6%.

4.7.4 Results

System	*Priority control*	*Annual diesel savings [€]*	*Total annual tap water/heating revenue [€]*	*Annual tap water/heating revenue pr household [€]*	*Payback time tap water/heating system [years]*	*COE/kWh thermal energy, 20 years lifetime [€]*
Scenario I	-	158487	-	-	-	-
Scenario II	One hour shift	177729	24601	241	19	0.075
Scenario III	One hour shift	177729	61591	604	6	0.030

It is important to specify that this is only a rough estimate. The biggest elements of uncertainty is the investment and installation cost. Secondly the economical model is simplified, and does not take into account maintenance cost and changes in energy price. Still, the results are interesting. Both scenario II and III turned out to be profitable compared to a pure fossil fuelled thermal system. The reason scenario III performed so much better than scenario II was that it didn't require any additional investments. In fact, scenario III would most likely be cheaper, because the simulations show that it might not require any additional storage elements to perform well.

One element that has not been included in the cost analysis is the increased windmill size of scenario II and III. The wind energy that was left after the electrical load had been covered was considered to have no alternative cost, meaning it would otherwise go to waste. In practice, the installation cost of a windmill is often more than 50% of the total cost, meaning it is common to oversize the WECS. However, some of this additional cost should be included in the thermal cost analysis.

The profitability of a pure wind-diesel system was not thoroughly investigated, but appears to have a good potential. The reduced annual diesel consumption corresponds to over 150 000 €, enough to maintain an investment of 1 800 000 € over a 20-years period at 6% interest.

5 Conclusions and Recommendations

The goal of this thesis was to investigate a renewable energy system where excess wind power was transformed and stored as thermal energy.

The west-Nordic region has numerous communities that are not connected to the central grid, and relies on their own electricity production. The electricity and heat generation is to a great extent based on fossil fuel. With the increasing focus on renewable energy and a steady rising oil price, there is a growing interest for renewable energy solutions both among the politicians and the local communities.

Energy consumption

The first part of the project was devoted to local energy planning of the community of Nólsoy. The yearly consumption and consumption profile of electricity and oil were identified. This included a comprehensive survey on buildings, utilities and energy consumption, handed out to every household on the island. The average energy consumption for a household on Nólsoy was estimated to 8395 kWh electricity and 3125 litres of fuel oil (28125 kWh gross).

Simulation results

Achieving a high share of renewable energy in a stand-alone system can be challenging. Wind power production is very fluctuating, and an energy storage element can greatly increase the amount of utilized energy. However, large scale storage of electricity is expensive and technically challenging. The idea investigated in this thesis was to convert the excess wind power to thermal energy in decentralized domestic hot water tanks, DHTs. DHTs are substantially cheaper than electricity storage devices such as batteries and hydrogen systems, and give the possibility of substituting some of the large amounts fossil fuel combusted for tap water and heating with renewable energy.

Three different energy scenarios based on a wind-diesel system were constructed and simulated in a transient simulation program (TRNSYS).

Scenario I was a classic wind-diesel system, and was mainly used as a reference. The good wind condition in the region, coupled with a good match between the wind- and the load profile resulted in a halving of the diesel consumption compared to the reference system with diesel generators. However, more than 50% of the wind energy had to be dumped.

In scenario II, the excess wind power was diverted to a thermal load controller which in turn controlled a number of distributed DHTs. These units were switched on and off to match the excess power according to a generated priority routine.

The simulation was run while varying tank parameters to study the effect on system performance. In general, increasing the storage tank size while holding the rated heating power within an interval from 750 – 1500 W gave the best results, while changing the tank temperature did not affect the system substantially. The overall best result from both a practical and a performance point of view was achieved with a tank size of 1 m^2 a heating element of 1000 W. At this setting the DHTs covered 75% of the tap water load, reducing the total oil consumption for tap water heating by 31023 litres.

Scenario III was similar to scenario II in layout, but instead of heating tap water the excess wind power was used to cover the space heating demand. Unlike scenario II, a small storage size and an increased heating element yielded the best results, more precisely 0.05 m^3 and 1500 W. At the most, 25% of the heat demand was covered by excess wind power, saving 77668 litres of oil.

The DHTs in scenario II and III were originally controlled by a temperature priority controller, meaning that the tank with the lowest water temperature was first in line to receive excess power. A disadvantage with this system is that it requires a two-way communication between the load controller and the distributed loads, increasing investment cost. The scenarios were therefore simulated with a simplified control system where the priority levels for each DHT were changed at a regular basis, something that only requires a one-way communication system. The results showed that this had this had negible effect on the system performance.

The cost of energy for the thermal energy supplied from the DHTs was estimated using the investment cost for the storage tanks, load controllers and communication utilities. Scenario III turned out to be most economical with a COE of 0.03 €/kWh, compared to 0.075 €/kWh for scenario II, with a payback time of 6 years and 19 years accordingly. Fuel oil is currently priced at around 0.079 €/kWh. The cost of energy figures are only approximations, but it seems clear that scenario III is the most economically viable one.

A pure wind-diesel system like scenario I can reduce the annual diesel consumption with an amount corresponding to over 150 000 € in fuel cost, enough to maintain an investment of 1 800 000 € over a 20-years period at 6% interest. Utilizing excess wind power in distributed domestic hot water tanks can help reduce the consumption of fossil fuel further, and at the same time be competitive on price compared to fuel oil.

Recommendations for further work

Simulation model

- One disadvantage with the simulation model was that only four DHTs were simulated in detail. This affected the amount of excess wind power that could be utilized, since the possibility of following the excess power closer is much greater with a higher resolution. One possibility for including more DHTs could be to write a new TRNSYS type in FORTRAN that can automatically control a larger amount of DHTs without demanding a manual configuration.
- The time detail could probably have been lowered to improve the simulation accuracy, but this requires a higher resolution on the input data for a full benefit.
- Include a safety dump load as a short-time buffer that can absorb fluctuations in the power.
- Use a complete yearly correlated wind profile in the simulations when it becomes available.

General

- Initialize a load measurement on the sub sea power cable in order to get better data for both the yearly and the 24 hours load curve.
- Monitor fuel oil level for a number of households in order to get a better yearly load profile for space heating (this has been started by Bjarti Thomsen in the spring 2006).
- Calculate the maximum heating power demand for the households using building data from the questionnaire.

6 Bibliography

- Hanssen, S. O. & Thue, J. V. & Skarstein, Ø. & Gjerstad, F. O. & Novakovic, V. (1996), Enøk I bygninger – Effektiv energibruk, Universitetsforlaget a/s.
- Larsen, B. M. & Nesbakken, R. (2005), Formålsfordeling av husholdningenes elektrisitetsforbruk i 2001, Statistisk Sentralbyrå.
- Sørensen, S. (1977), Energy consumption for hot water supply, CIB Commission W 62.
- Cappelen, J. & Laursen, E. V. (2004), The climate of the Faroe Islands – with climatological standard normals, 1961-1990, Danish Meteorological Institute.
- Lemgart, M.-L. & Ulleberg, Ø. (2005), Muligheter for fornybare energisystemer og hydrogenteknologi i vest-norden, ECON & IFE.
- SEV (2006), The Faroe Islands' public energy company, personal contact , web page (Http://www.sev.fo).
- Shell (2006), web page (Http://www.shell.fo)
- Cotrell, J. & Pratt, W.(2003), Modeling the feasibility of using fuel cells and hydrogen internal combustion engines in remote renewable energy systems, presented to the American Wind Energy Association's 2003 WINDPOWER Conference, Austin, Texas, National Renewable Energy Laboratory
- Drouilhet, S. & Shirazi, M. (2002), Alaska High-Penetration Wind-Diesel Hybrid Power System: Theory of Operation. NREL/TP-500-31755. Golden, CO: National Renewable Energy Laboratory, May 2002.
- Johnson, C. & Abdulwahid, U. & Manwell, J.F. & Rogers, A. (2002), Design and modelling of dispatchable heat storage in wind/diesel systems, Renewable Energy Research Laboratory, Dept. of Mechanical and Industrial Engineering, University of Massachusetts, Amherst, MA 01003.
- Hunter, R. & Elliot, G. (1994), Wind-Diesel Systems: A Guide to the Technology and its Implementation, Cambridge, Cambridge University Press.
- Drouilhet, S.M. (1999), Power Flow Management in a Wind-Diesel Hybrid Power System with Short-Term Energy Storage, Windpower '99, Burlington, VT, AWEA.
- Strømmen, K. (2005), Decentralized energy supply based on renewable energy sources, Department of Electrical Engineering, NTNU.
- Hagstova Føroya (2005), Faroe Islands' Statistics Department, web page, (Http://www.hagstova.fo).
- SSB, Statistisk Sentralbyrå (2006), web page, (Http://www.ssb.no).
- UNSD, United Nations Statistics Division (2005), Dioxyde de carbone (CO_2), émissions en tonnes de CO2 par personne (CDIAC), web page, (Http://millenniumindicators.un.org/unsd/mifre/mi_series_results.asp?rowID=751\&fID=r15\&cgID=).
- Züttel, A., Hydrogen storage methods and materials, University of Fribourg

- Skrecc, Sout Kentucky Rural Electric Cooperative Corporation (2006), web page, (Http://www.skrecc.com/ets.htm).
- CEC, Clark Energy Cooperative (2006), web page, (Http://www.clarkenergy.com/ets.phtml).
- Wikipedia (2006), web page, (Http://en.wikipedia.org/wiki/Power_line_communication), (Http://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity).
- Rekstad, J. (2000), Utnyttelse av solenergi til oppvarming, Faglærer-seminar NTNU den 4.4 2000.
- Jacobsen, A.(2005), Master Thesis
- HYDROGEMS (2005), Institutt for Energiforskning, web page, (Http://www.hydrogems.no).
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7 Appendix

7.1 Appendix I - Simulation configuration

7.1.1 System settings

All changes from the basic configurations are marked as **bold.**

Scenario I - Wind-Diesel: Basic configuration

	Value	**Denom**	**Description**
Pmax_EL	265000	KW	Maximum (hourly) electric power load
Pmax_Heat	500000	KW	Maximum (hourly) thermic power load
Prated_DEGS	100	KW	Rated power of the diesel generator
Pmax_DEGS	Prated_DEGS*1.2		
Pmin_DEGS	Prated_DEGS*0.4		
Nmin_DEGS	1		Lowest number of diesel generators allowed
Nmax_DEGS	5		Highest number of diesel generators allowed

Scenario II - Wind-Diesel-DHT: Basic configuration

	Value	**Denom**	**Description**
T_tap	65	C	The desired temperature for tap water
T_source	10	C	Temperature of the water source
Etap_year	3794*3600*Nhouseh_DHT	KJ	Total yearly energy consumption for tap water
PdumpUnitRatio	1/102		The share of the excess wind energy available per DHT
P_DHT	2000	W	Rated power of the DHT
P_DHT_hr	P_DHT*3.600	KWh	
V_DHT	1	m^3	Tank volume of the DHT
Nhouseh_DHT	1		Number of households per DHT
Pmax_EL	265000	KW	Maximum (hourly) electric power load
Tset_DHT	85	C	Set temperature for DHT
DB_DHT	5	C	Temperature deadband for DHT
Prated_DEGS	100	KW	Rated power of the diesel generator
Pmax_DEGS	Prated_DEGS*1.2		
Pmin_DEGS	Prated_DEGS*0.4		
Nmin_DEGS	1		Lowest number of diesel generators allowed
Nmax_DEGS	5		Highest number of diesel generators allowed
Cp_water	4.186	KJ/kg	
Qavg_hour	(Etap_year/8760)/(Cp_water*(T_tap - T_source))	litre/hr	Average tap water consumption per hour
T_envi	15	C	Environment temperature
T_init	65	C	Initial temperature of water in DHT

Scenario II - Wind-Diesel-DHT: Reference system

	Value	**Denom**	**Description**
P_DHT	**0**	W	Rated power of the DHT
T_envi	**10**	C	Environment temperature

T_init	**10**	C	Initial temperature of water in DHT

Scenario II - Wind-Diesel-DHT: Default settings

	Value	**Denom**	**Description**
T_envi	**10**	C	Environment temperature
T_init	**10**	C	Initial temperature of water in DHT
Hnode_DHT	**1.0839/Nnode_DHT**	M	Height of the nodes in the DHT

Scenario II - Wind-Diesel-DHT: Storage tank volume

	Value	**Denom**	**Description**
V_DHT	**0.25-3**	m^3	Tank volume of the DHT
T_envi	**10**	C	Environment temperature
T_init	**10**	C	Initial temperature of water in DHT
Nnodes_DHT	**15**		Number of temperature nodes in the DHT
Hnode_DHT	**(0.68-1.56)/Nnode_DHT**	M	Height of the nodes in the DHT

Scenario II - Wind-Diesel-DHT: Maximum heating rate of DHT

	Value	**Denom**	**Description**
P_DHT	**500-5000**	W	Rated power of the DHT
T_envi	**10**	C	Environment temperature
T_init	**10**	C	Initial temperature of water in DHT
Nnodes_DHT	**15**		Number of temperature nodes in the DHT
Hnode_DHT	**1.08/Nnode_DHT**	M	Height of the nodes in the DHT

Scenario II - Wind-Diesel-DHT: Temperature settings

	Value	**Denom**	**Description**
Tset_DHT	**65-95**	C	Set temperature for DHT
DB_DHT	**2.5-5-7.5**	C	Temperature deadband for DHT
Prated_DEGS	**1000**	KW	Rated power of the diesel generator
T_envi	**10**	C	Environment temperature
T_init	**10**	C	Initial temperature of water in DHT
Nnodes_DHT	**15**		Number of temperature nodes in the DHT
Hnode_DHT	**1.08/Nnode_DHT**	M	Height of the nodes in the DHT

Scenario III - Wind-Diesel-DHT (heating): Reference system

	Value	**Denom**	**Description**
PdumpUnitRatio	1/102		The share of the excess wind energy available per DHT
P_DHT	**0**	W	Rated power of the DHT
P_DHT_hr	P_DHT*3.600	KWh	
V_DHT	1	m^3	Tank volume of the DHT
Nhouseh_DHT	1		Number of households per DHT
Pmax_EL	265000	KW	Maximum (hourly) electric power load
Pmax_Heat	500000		
Tset_DHT	85	C	Set temperature for DHT

DB_DHT	5	C	Temperature deadband for DHT
Prated_DEGS	100	KW	Rated power of the diesel generator
Pmax_DEGS	Prated_DEGS*1.2		
Pmin_DEGS	Prated_DEGS*0.4		
Nmin_DEGS	1		Lowest number of diesel generators allowed
Nmax_DEGS	5		Highest number of diesel generators allowed
Cp_water	4.186	KJ/kg	
Qavg_hour	(Etap_year/8760)/(Cp_water* (T_tap - T_source))	litre/hr	Average tap water consumption per hour
T_envi	10	C	Environment temperature
T_init	20	C	Initial temperature of water in DHT
Nnodes_DHT	15		Number of temperature nodes in the DHT
Hnode_DHT	1.08/Nnode_DHT	M	Height of the nodes in the DHT
T_radiator	65	C	Temperature of the water going to the radiators
Eheat_year	28125*3600*Nhouseh_DHT	KJ	The total heating demand per household per year
Pavg_hour	Eheat_year/8760	KJ	Average heating demand per hour
Qheatavg_hour	200	litre/hour	Flow rate of water in the radiator circuit
T_indoor	20	C	Indoor temperature

Scenario III - Wind-Diesel-DHT (heating): Default settings

	Value	**Denom**	**Description**
P_DHT	**1000**	W	Rated power of the DHT

Scenario III - Wind-Diesel-DHT (heating): Storage tank volume

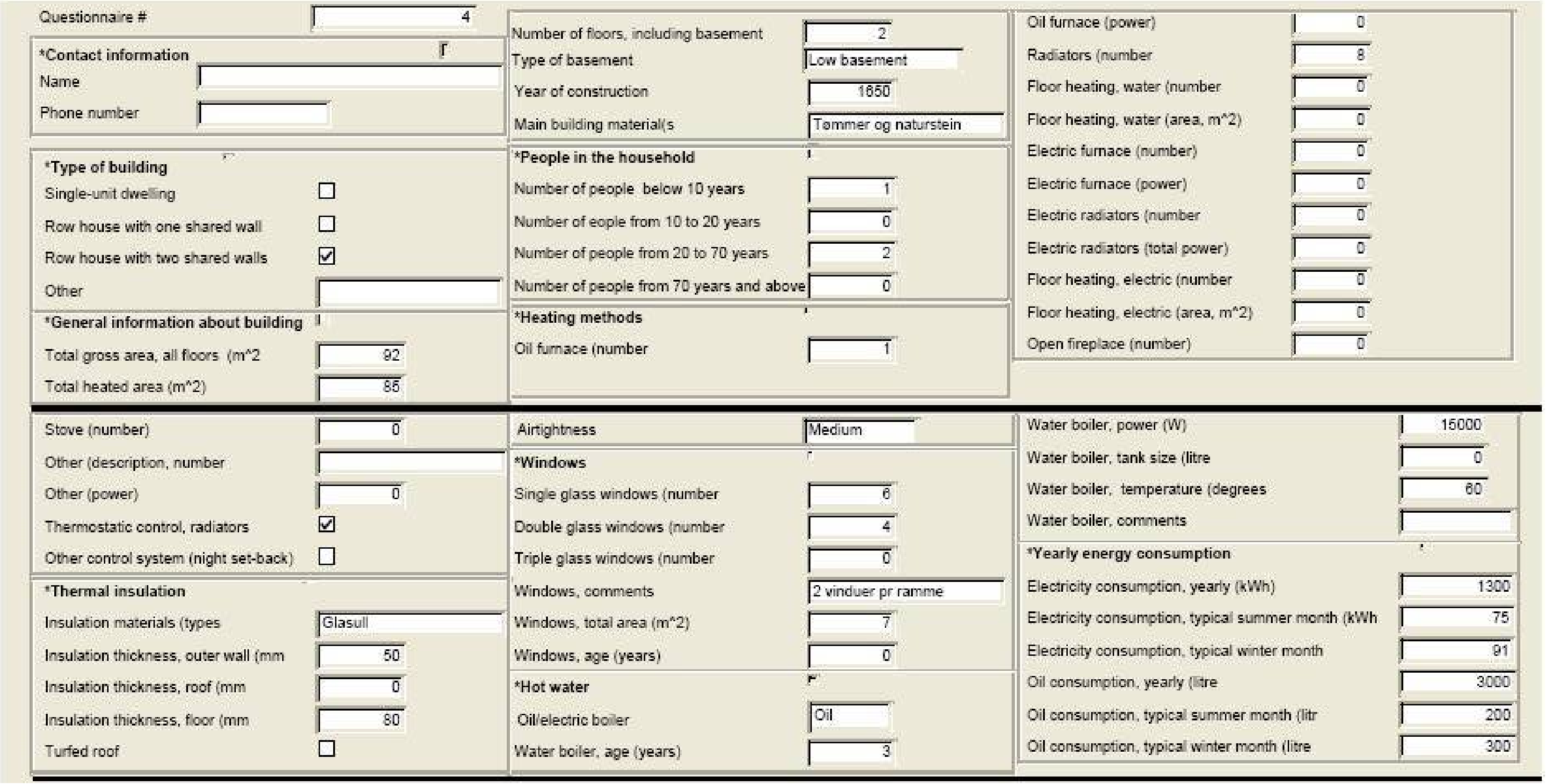
	Value	**Denom**	**Description**
P_DHT	**1000**	W	Rated power of the DHT
V_DHT	**0.05-3**	m^3	Tank volume of the DHT

Scenario III - Wind-Diesel-DHT (heating): Maximum heating rate of DHT

	Value	**Denom**	**Description**
P_DHT	**500-6000**	W	Rated power of the DHT
V_DHT	**0.5**	m^3	Tank volume of the DHT

7.2 *Appendix II – Questionnaire*

Note that this is not the original design of the questionnaire, only the template for adding data to the database. The questions are however identical (translated to English).



Questionnaire #	4
***Contact information**	
Name	
Phone number	
***Type of building**	
Single-unit dwelling	☐
Row house with one shared wall	☐
Row house with two shared walls	☑
Other	
***General information about building**	
Total gross area, all floors (m^2	92
Total heated area (m^2)	86

Number of floors, including basement	2
Type of basement	Low basement
Year of construction	1850
Main building material(s	Tømmer og naturstein
***People in the household**	
Number of people below 10 years	1
Number of eople from 10 to 20 years	0
Number of people from 20 to 70 years	2
Number of people from 70 years and above	0
***Heating methods**	
Oil furnace (number	1

Oil furnace (power)	0
Radiators (number	8
Floor heating, water (number	0
Floor heating, water (area, m^2)	0
Electric furnace (number)	0
Electric furnace (power)	0
Electric radiators (number	0
Electric radiators (total power)	0
Floor heating, electric (number	0
Floor heating, electric (area, m^2)	0
Open fireplace (number)	0

Stove (number)	0
Other (description, number	
Other (power)	0
Thermostatic control, radiators	☑
Other control system (night set-back)	☐
***Thermal insulation**	
Insulation materials (types	Glasull
Insulation thickness, outer wall (mm	50
Insulation thickness, roof (mm	0
Insulation thickness, floor (mm	80
Turfed roof	☐

Airtightness	Medium
***Windows**	
Single glass windows (number	6
Double glass windows (number	4
Triple glass windows (number	0
Windows, comments	2 vinduer pr ramme
Windows, total area (m^2)	7
Windows, age (years)	0
***Hot water**	
Oil/electric boiler	Oil
Water boiler, age (years)	3

Water boiler, power (W)	15000
Water boiler, tank size (litre	0
Water boiler, temperature (degrees	60
Water boiler, comments	
***Yearly energy consumption**	
Electricity consumption, yearly (kWh)	1300
Electricity consumption, typical summer month (kWh	75
Electricity consumption, typical winter month	91
Oil consumption, yearly (litre	3000
Oil consumption, typical summer month (litr	200
Oil consumption, typical winter month (litre	300