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RENEWABLE ENERGY SYSTEM CONCEPTS FOR NÓLSOY, THE FAROE ISLANDS

Institute for Energy Technology

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Summary

In 2003 the Nordic Council of Ministers, together with partners from Iceland, Greenland and the Faroe Islands granted the funding for a feasibility study on renewable energy systems and hydrogen energy technology for remote areas in the West Nordic region. The specific objective with this report, which is part of the larger study, was to propose and evaluate renewable energy system concepts suitable for the island of Nólsoy at the Faroe Islands. The method used was to:

(1) Estimate the wind energy potential at Nólsoy.
(2) Determine the electrical and thermal energy demands based on statistical data and a energy survey performed at Nólsoy in 2006.
(3) Compare the cost-effectiveness of wind/diesel generator system mini-grid configurations to existing diesel-only configurations.
(4) Study the technical feasibility of storing excess wind energy in distributed domestic hot water tanks for heating purposes.
(5) Evaluate the technical and economical potential for installing alternative heat pump systems.
(6) Evaluate the possibility of integrating a hydrogen energy system into a future stand-alone wind/diesel mini-grid system at Nólsoy.

The main conclusion so far (final project conclusions to be made in 2007) is that the installation of wind/diesel mini-grid system at Nólsoy is both technically and economically viable, particularly if some of the excess wind energy is used to meet the local space heating demands.

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List of Acronyms

Acronym	Description
AC	Alternating Current
COE	Cost of Energy
DEGS	Diesel Engine Generator System
DHT	Domestic Hot Water Tank (often referred to as DHWT)
DMI	The Danish Meteorological Institute
ECON	Economic and energy consultant company
H_2	Hydrogen
HP	Heat Pump
HYDROGEMS	Hydrogen energy models library
ICE	Internal Combustion Engine
IFE	Institute for Energy Technology
NTNU	Norwegian University of Science and Technology
PEM	Proton Exchange Membrane (as in PEM fuel cells)
PV	Photovoltaic
SEV	Local power company at the Faroe Islands
TRNSYS	Transient system simulation program
UPS	Uninterrupted Power Supply
WECS	Wind Energy Conversion System

1 Introduction

1.1 Objective

The objective with this interim report (for Phase II of the project) is to propose, describe, and evaluate various technical concepts for a renewable energy system suitable for the island of Nólsoy at the Faroe Islands.

1.2 Background (Project Phase I)

In 2003 the Nordic Council of Ministers, together with partners from Iceland, Greenland and the Faroe Islands granted the funding for a feasibility study on renewable energy systems and hydrogen energy technology for remote areas in the West Nordic region [1].

The feasibility study, performed in the period 2003-2004 by ECON (Denmark) and Institute for Energy Technology (IFE, Norway), was divided into two parts: (1) Energy planning and (2) System Analysis. The first part of the study focused on mapping the structure of the energy systems, energy production, and energy use in Iceland, Greenland, and the Faroe Islands. A set of possible locations for renewable energy systems in the three countries was also identified. In part two of the study three case studies (one for each country) on possible system configurations were performed using constructed load and weather data and a set of detailed renewable system energy modeling tools. More information (in Danish and Norwegian) about this work is found in the final report [1].

1.3 Overview (Project Phase II)

In 2005 it was decided to start up a second phase of this project with more focus on two specific locations: (1) Nólsoy, the Faroe Islands and (2) Nanortalik, South Greenland. The overall objective of Phase II of the project was to gather more detailed information on wind energy and energy demand for the two sites and to develop more pinpointed system concepts for each location. In order to achieve this, proper wind energy monitoring equipment had to be installed and thorough energy audits needed to be performed at the two sites.

Nólsoy is a 10 km^2 island located ca. 5 km east of the capital city of Tórshavn. Nólsoy was chosen because of its potential for high wind energy capture, proximity to Tórshavn (practical consideration), reasonable size (100 households), and representative population mix (ca. 270 people, hereof 70 people below 20 years of age and a large portion fit for work). There used to be a fishery at the island, but this was shut down in 2003. However, Nólsoy is still a vital local community, and new houses are being built on the island. The Faroese government and local community have shown a great interest in developing a project at Nólsoy. The village has a school, a childcare center, a café, and a ferry with regular departures for people that commute to work and school in Tórshavn. The power system at Nólsoy, operated by the national power company SEV, currently consist of a 10 kV sea cable (connected to main island grid), a transforming station for the local mini-grid (400 V), and two back-up diesel generators (each at 320 kVA, or 256 kW) (Figure 1).

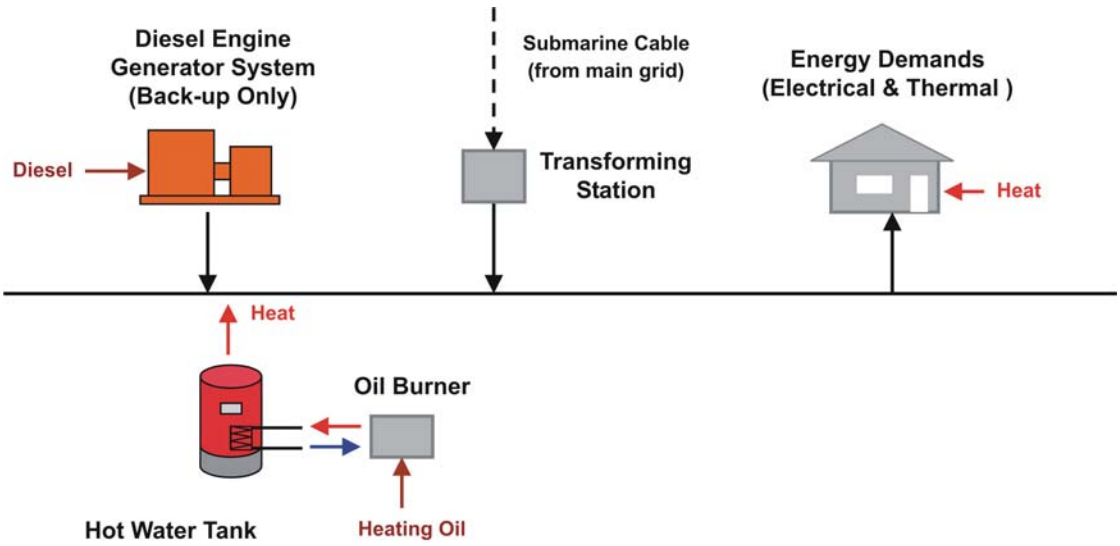

Figure 1 Schematic of existing (2006) energy system in place at Nólsoy.

Nanortalik is a small town located at the outlets of the two fjords Sermilik and Tasermiut Kangerluat in the southern part of Greenland, not far away from Cape Farewell. The town, with a population of 1 550 inhabitants, has a school, college, hospital, heliport, museum, several shops and supermarkets, and two hotels. The municipality of Nanortalik includes a number of villages with a total population of ca. 1 000. The shrimp factory located at the quay was closed in 2001, but has later been replaced by a crab factory. There is also a sealskin factory in the town. The future development of the new work places is uncertain, but the gold mine located ca. 30 km northeast of Nanortalik could contribute to new development. Over the past few years there has been an increased immigration of people coming from the villages around Nanortalik, and this is likely to continue. In 2005/2006 the national power company Nukissiorfiit rebuilt the diesel engine power station in Nanortalik, which now consists of three main generators (1080 kW (old unit) + 680 kW + 510 kW (new units)) and two peak power generators (2 × 370 kW).

In order to perform more detailed technical studies on possible renewable energy system concepts for Nólsoy and Nanortalik in Phase II of the project, more detailed wind energy and load data than available in Phase I of the project was required. Over the course of the project it became apparent that the data collection would be much easier in Nólsoy than in Nanortalik, partly because of a local community engagement and partly because of geographic accessibility (Nólsoy is less remote than Nanortalik). The West Nordic project group therefore decided to focus the technical system concept development based on data and information from Nólsoy. However, it should be noted that a similar system concept development is planned being performed for Nanortalik in Phase III of the project, as soon as more data is available. This report aims at summarizing the main findings for the Nólsoy case study. The method and tools developed can readily be applied to a case study similar to Nanortalik.

1.4 Meetings and Site Visits

Several site visits have been made in order to get a better understanding of the local renewable energy resources and energy mix (electrical and thermal). In May 2005, the project group made a site visit to Nólsoy (Figure 2), as part of the project Phase II kick-off meeting. In August 2005 two members of the project group (from ECON and IFE) made a site visit to Nanortalik (Figure 3). More details on the general work performed in Phase II of the West Nordic project and the specific Nólsoy and Nanortalik project development are reported in a separate status report (in Danish) written by Marie-Louise Lemgart [2].

In September 2005 a site visit was made to Hydro's wind/hydrogen demonstration system at the Utsira island in Norway (Figure 4). This visit gave members from the project group (Nordic Energy Research, ECON, and IFE) and people involved in the projects in Greenland and the Faroe Island (including people from the local community at Nólsoy) a chance to get first-hand information about the technology.

In May 2006 a Masters student from Norwegian University of Science and Technology (NTNU) visited Nólsoy for two weeks. The main objective with this field trip was to get a close interaction between the local community at Nólsoy and the West Nordic project group. An energy survey was also carried out among the local islanders in order to quantify the energy consumption on the island, particularly the thermal energy demand.

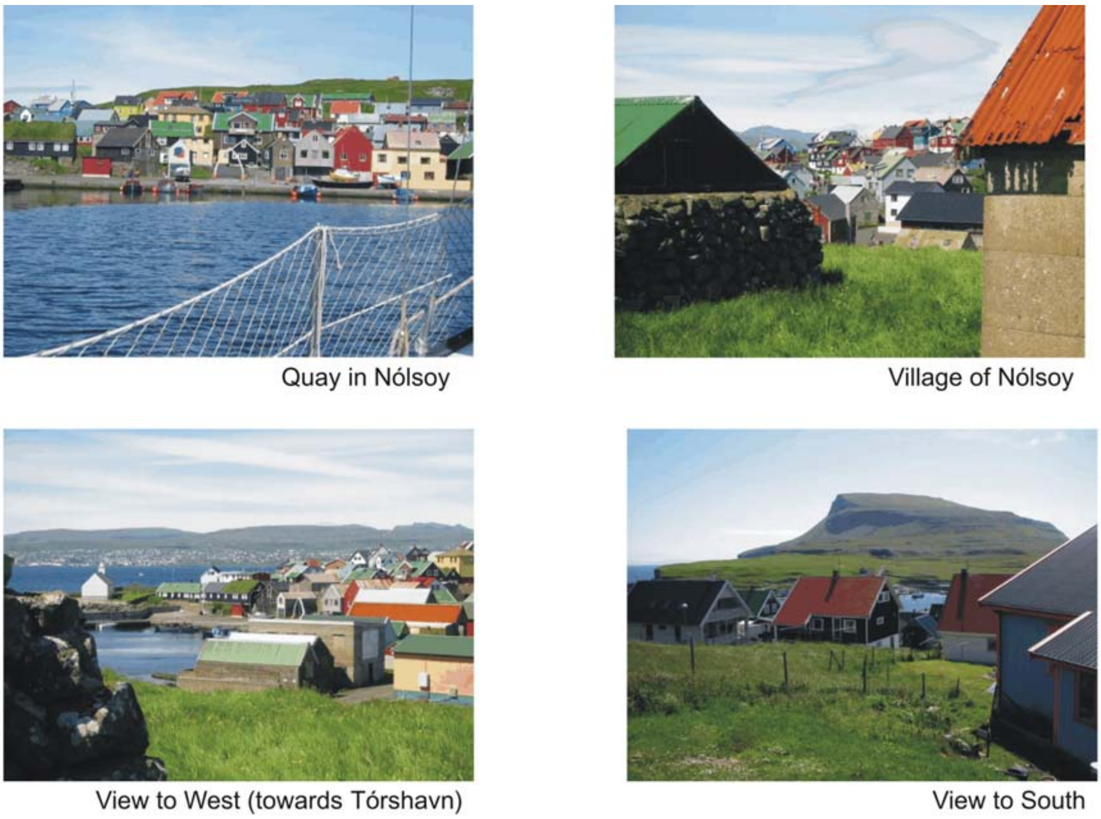

Figure 2 Nólsoy, the Faroe Islands (Photos: www.faroeislands.dk)

Figure 3 Nanortalik, South Greenland (Photos: Ø.Ulleberg, 2005)

Figure 4 Utsira (Norway) wind/hydrogen energy demonstration system (Photos: Ø. Ulleberg, 2005)

1.5 Scope of Work (Project Phase II)

This technical report is part of a larger study on the feasibility of renewable energy and hydrogen technology for the distributed energy systems in the West-Nordic region [1]. More information about the general status of the progress made in Phase II of the project is found in a separate status report [2]. The scope of work for the technical evaluations performed in Phase II of the project was:

- Estimate the wind energy potential at Nólsoy based on preliminary wind energy measurements made on site at Nólsoy and long-term data from Mykines Fyr (DMI)
- Determine the electrical and thermal energy demands at Nólsoy based on statistical data from the local power company (SEV), the oil suppliers (Statoil and Shell), and a user survey at the island
- Compare the cost-effectiveness of wind/diesel generator system mini-grid configurations to the existing diesel-only configurations
- Study in detail the technical feasibility of using excess wind energy to meet the tap water and space heating demands, either directly through the use of distributed domestic hot water tanks (DHTs), or by using heat pumps
- Evaluate the possibility to integrate stationary hydrogen energy systems into an optimized wind/diesel mini-grid system

2 Overall System Concept

A schematic of the overall renewable energy hydrogen system concept proposed for Nólsoy is provided in Figure 5.

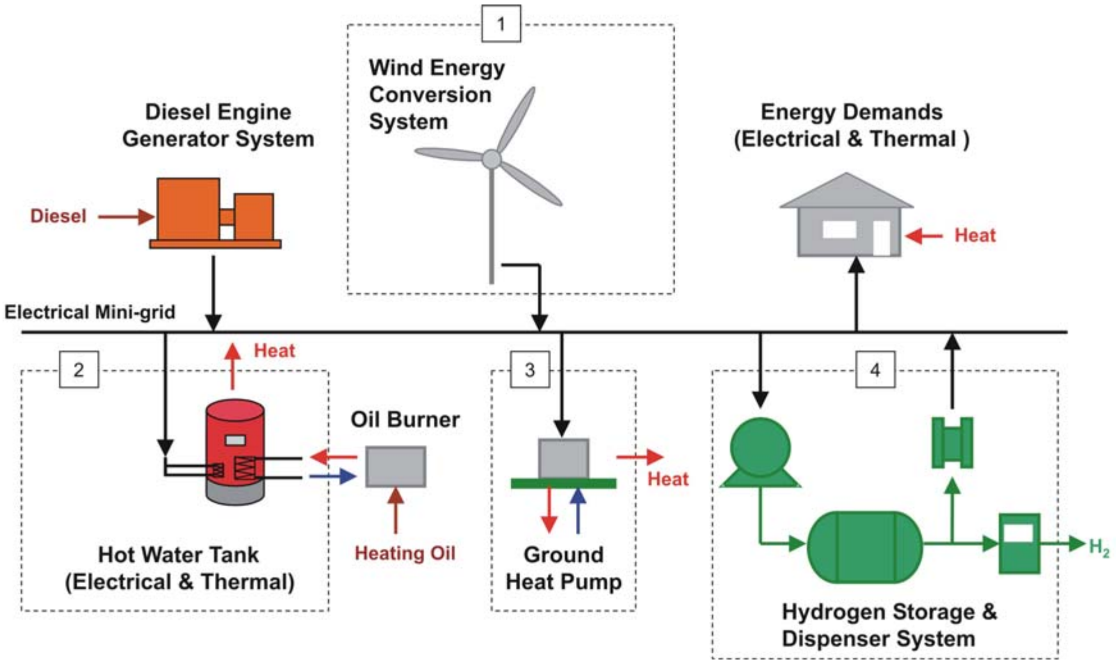

Figure 5 Overview of proposed renewable energy system concept for Nólsoy, where each sub-system (1 to 4) is added to the reference system (diesel engine and oil burner) in the given order (1 to 4).

2.1 System Description

The basic concept for the power system is to add a wind energy conversion system (WECS) (System 1) to the mini-grid using the diesel engine generator system (DEGS) as the main back-up power, and allow for stand-alone operation (independent of the main electrical grid). A stand-alone mini-grid is proposed instead of a system based on the existing sea cable because of higher potential for a fully integrated electrical power and thermal energy system.

The basic thermal concept for the system is to replace the existing domestic hot water tanks (DHTs). These are based on heating oil with controllable distributed DHTs that allow for heating from different energy sources (System 2). Distributed domestic multi-source (electrical and thermal) DHTs can utilize excess wind power and existing heating oil infrastructure, and have the potential to meet both the hot tap water energy demand (ca. 65°C) and the space heating demands (radiators at ca. 85°C).

A ground heat pump (HP) (System 3) is most suitable if it can be combined with a low-temperature floor-heating system (ca. 35-40°C). Hence, a heat pump system is only proposed for a dedicated building, namely the childcare center.

A hydrogen storage and dispenser system consisting of a water electrolyzer, hydrogen storage, fuel cell, and dispenser (System 4), will be the least energy and cost-efficient part of the system, particularly if the focus is to meet stationary power demands. Hence, a system that maximizes the hydrogen production in an electrolyzer and minimizes the required storage by making use of hydrogen in local power applications (e.g., uninterrupted power supply) and local transport (e.g., small boats, scooters, electric vehicles) is proposed.

2.2 Project Stages

The following five project stages are recommended for the development and implementation of the system concept described in Figure 5:

1. **Energy efficiency actions**: Insulate walls and roofs, replace windows (if needed), etc. The local authorities at Faroe Islands should give financial incentives for various energy efficiency measures before the main project starts.

2. **DEGS**: Replace the existing diesel engine generators (DEGS), currently only used as back-up for the sea cable, with new and more modern DEGS that allow for stand-alone operation with a wind energy conversion system (WECS). Hence, the DEGS-installation is closely related to a future WECS-installation.

3. **WECS**: Install a fully integrated commercial wind/diesel stand-alone mini-grid AC solution (System 1). There exist today fully commercial WECS/DEGS-mini-grid solutions. Hence, the challenge is mainly to get the financing. One logical financial model is that the local community establishes a co-operation (co-op) so that the users own the energy system themselves.

4. **DHT**: Replace existing domestic hot water tanks (DHTs) with new and larger super-insulated multi-source DHTs that allows for conversion of excess wind energy to thermal energy. Configure DHTs and control system for combined electrical (only excess wind power, not diesel power) and thermal heating (heating oil); this requires communication between DHTs and a centralized control system. Financial incentives for installing new DHTs could be provided by the authorities at Faroe Islands.

5. **HP**: Install a heat pump system suitable for a user with a relatively large thermal demand and a need for high-quality indoor climate (e.g. the school or childcare center). This installation could be made at an earlier stage, but in order to ensure that the heat pump is running mainly on wind power it should be installed after the overall wind/diesel mini-grid is in place. A one-time grant to reduce some of the investment costs for the heat pump may be needed.

6. **H_2-system**: The installation of a hydrogen system should only be done after all of the abovementioned actions have been performed and installations have been made. The build-up of a hydrogen project should be closely linked with the Faroese government's plans for more environmental friendly transport in the (e.g. maritime sector). This means that detailed plans must be made on how to use the hydrogen (and oxygen) produced on the island in the best possible way. Joint-funding within EU's7th framework program should be sought in 2007.

3 Energy Demands

3.1 Electrical Energy Demands

An overview of the annual electricity demand at Nólsoy made available by the national power company SEV [3] is shown in Table 1. The statistics clearly shows the drop (ca. 50%) in electricity demand from 2003 to 2004 due to the closing of the fish farm. The total annual electricity consumption at Nólsoy is today about 670 MWh, where about 440 MWh (65%) is used in the households. This gives about 4400 kWh per household, which is in quite good agreement with the result (3700 kWh) from the energy survey (Table 2).

Table 1 Annual electricity consumption at Nólsoy 2002-2005[3]

Type of Electricity Demand	**2002**	**2003**	**2004**	**2005**
Fish farms	631 680	521 520	17 136	21 012
Public buildings	82 855	80 363	76 431	79 139
Building activity	3 891	3 924	83	598
Fishery	4	46	447	2 069
Transport, post & communication	49 336	51 049	56 403	48 914
Street lightning	35 194	30 548	37 978	37 163
Trade, accommodation and restaurant	33 368	31 205	31 559	37 998
Church and bethel	1 289	1 215	1 425	1427
Agriculture	2 474	2 318	2 164	2039
Culture and spare time	3 326	2 923	2 607	3368
Boat houses	2 307	1 997	1 509	1555
Households	421 422	411 151	450 360	429 712
Reconditioning etc	722	620	977	592
Total Electricity Demand (kWh)	**1 267 868**	**1 138 879**	**679 079**	**665 586**

It took some time before the correct electricity statistics (Table 1) for Nólsoy was established. For this reason different load profiles for the system analysis were used in the system simulations performed at IFE and in the Masters study at NTNU [4]. Actually, the value for the total electricity demand used in the Masters study was about twice the value used by IFE, who based their calculations on the year 2005 in Table 2. This makes it impossible to compare the simulation results directly. However, since the Masters study mainly focused on the thermal side of the proposed system concept (Figure 5) and the possible integration of distributed domestic hot water tanks (DHTs), the conclusions from the Masters study can be interpreted independently from the rest of the work performed within Phase II of this project.

The electrical mini-grid (400 V) at Nólsoy is today supplied with power from a transforming station connected to a sea cable (10 kV) from Tórshavn. This means that detailed measurement of the hourly (or minutely) electrical power consumption on the mini-grid could be made. Unfortunately, no such measurements of electrical power consumption at Nólsoy are currently being made. However, the power company SEV has promised to do some measurements, and make these available to the project at a later stage, hopefully by the end of 2006.

Thus, for simulations performed in Phase II of this project a normalized electrical load profile generated in Phase I of the project was used [1]. This profile was based on data from Grímsey, Iceland, which is an island community similar to Nólsoy, but slightly smaller. Figure 6 shows the monthly electrical demand profile used in the system simulations performed at IFE, while Figure 7 shows a representative daily electricity load profile for Nólsoy.

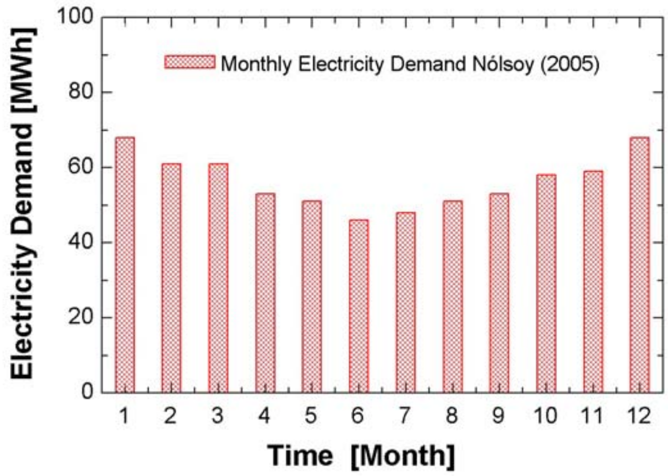

Figure 6 Monthly electricity energy demand for entire mini-grid at Nólsoy

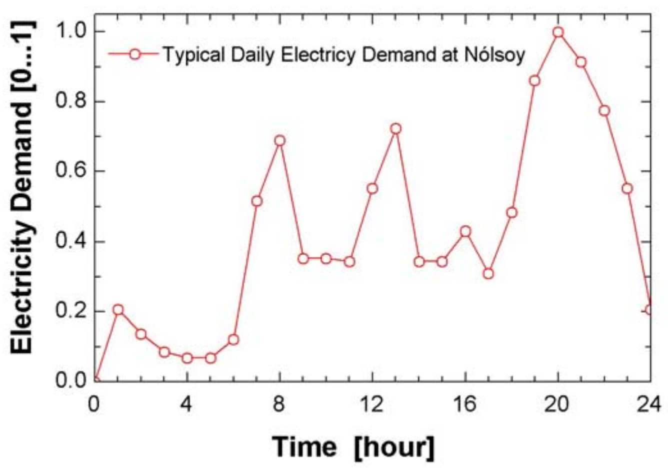

Figure 7 Typical daily electricity demand for Nólsoy.

3.2 Thermal Energy Demands

It is quite difficult to estimate the thermal energy demand for local communities in the Faroe Islands because oil is used for both heating and for transport. This is exactly the case at Nólsoy, where oil is used in domestic oil burners for heating and as fuel for private boats.

The chosen method for collecting thermal data in this project was to obtain records of the quantity oil delivered to households at Nólsoy from the two oil companies at the Faroe Islands (Statoil and Shell), and perform statistical analysis on the data. A local survey with the aim to map the existing local energy infrastructure on the island was also performed. This survey did provide some useful insight to the oil data made available. A detailed description of the survey and subsequent data analysis is available in a separate study [4], and only the main conclusions are summarized below in this report.

A typical household in the Faroe Islands uses approximately 4000 liters of oil per year [5]. If one assumes that all of this goes to heating purposes this corresponds to about 36000 kWh_{th} of net heating (assuming an oil burner efficiency of 90%). Incidentally, this estimate would result in an overall oil consumption at Nólsoy of 400 000 liter per year.

The estimate of 36000 kWh_{th} for heating per household per year seems too high. In comparison the average heating demand (2000-2004) for a household connected to the district heating system in Tórshavn is about 20300 kWh_{th} per year, which would correspond to 2230 liters of heating oil. Another comparison can be made between the Faroe Islands and Norway, where the total energy consumption for an average household in 2001 (single dwelling) was 27000 kWh_{th} [6]. Furthermore, in Tórshavn the there are on average 3600 degree-days per year, while Oslo (located on a similar latitude) observes on average 4177 degree days per year. The high average wind speeds at the Faroe Islands could make the heating demand higher than the number of degree-days suggest. Due to the temperate climate and long heating season, heating systems at the Faroe Islands are likely to be operating at lower efficiencies than those in southern parts of Norway.

A closer look at the oil sales statistics made available by Statoil and Shell showed that the average household oil consumption at Nólsoy for the period 2000-2005 was around 3125 liters. This is well above the average consumption in a dwelling in Tórshavn (ca. 2230 liters), but also well below the first estimate (4000 liters). In comparison, the average oil consumption in the households that participated in the survey was 2964 liters per year. Hence, the conclusion is that the average annual household heating oil consumption at Nólsoy is around 3000 liters, which corresponds to 27000 kWh_{th}.

The average annual hot tap water demand depends mainly on the number of people in the household. In an ordinary Norwegian household the hot tap water consumption is about 66 liters per day per person [7]. The average number of persons per household in Nólsoy was 2.7 persons, which yields an average household hot water consumption of ca. 180 liters per day. This yields a total hot water energy consumption of approximately 4000 kWh_{th}/year (assuming a constant feed water temperature of 5°C and an average tank temperature of and 65°C) [4]. This is equal to about 15% of the total heating demand, which compares well with the Norwegian average of 15-20% [8].

3.3 Energy Survey

In April-May 2006 a survey was conducted at Nólsoy with the aim to get a better overview of the local energy infrastructure, particularly the thermal energy demand. Another important objective with the survey was to interact with the local community and the end users, so that they could be made aware of the overall project and later on able to join in the further planning of the project. The survey was designed to gather information in the following five areas:

1. **General building information**: Type of house (single unit, row house), shape, size, heated area, year of construction and type of basement, if any

2. **Heating methods**: List of the household's heating methods, including electrical heaters and floor heating, and description of hot water boilers

3. **Thermal insulation**: Thermal insulation materials and thickness, number and area of windows, and number of layers in windows

4. **Electrical equipment**: A list of the number typical electrical appliances, including light bulbs

5. **Energy consumption**: Annual total energy consumption for most common energy sources used in household, including typical consumption during winter and summer month. (Data for other spaces, such as boat houses and sheep cots were given a separate post)

The original form of the questionnaire for the energy survey was developed by Øystein Ulleberg and Eva Rosenberg at IFE. This was then personally brought forward by Kristian Strømmen (Master student, NTNU) to two local contacts Nólsoy, Bjarti Thomsen and Dávur Juul Magnussen, who revised and adjusted the questionnaire for local conditions, and translated it to Faroese. (A copy of the front-end of the database for the survey is provided in the Appendix). The questionnaires were given to the end users on 28 April 2006. After one week only 25 out of 100 households had completed the questionnaire. After one month 35 questionnaires had been completed, where 29 were from private households. Out of these only 26 questionnaires were filled out in satisfactory manner.

The main results from the survey are summarized in Table 2, which shows that the average house is quite small (108 m^2) and old (1957). Most of the households (almost 100%) use oil-based domestic hot water tanks (184 liters), which typically are rated at 20 kW. The average annual oil consumption is ca. 3000 liters, or ca. 27000 kWh_{th}, while the annual average electricity consumption is ca. 3700 kWh_{el}. This gives a total average energy demand of ca. 30000 kWh_{th}, or ca. 280 kWh/m^2. In comparison, a large (> 150 m^2) Norwegian household uses on average ca. 170 kWh/m^2 [6]. This large difference can only be explained by the fact that the average building at Nólsoy is fairly old and poorly insulated compared to more modern houses. This in combination with a high wind chill factor is probably causing the relatively high overall heating demand.

Table 2 Summary of energy survey at Nólsoy performed in April/May 2006

Item	Value	Unit
Number of single unit dwellings	28	-
Average total heated area	108	m^2
Average total area	150	m^2
Average year of construction	1957	-
Average number of radiators	8	-
Average insulation thickness	13	cm
Number of oil based DHT heaters	24	-
Number of electric based DHT heaters	1	-
Average age of DHT heaters	17	-
Average DHT heater capacity	20	kW_{th}
Average DHT volume	184	litres
Average annual electricity consumption	3 677	kWh
Average annual oil consumption	2 954	litres
Average number of freezers	1.5	-
Average freezer capacity	512	litres

Average values are based on answers from 26 of 100 households

About 25% of the households at Nólsoy participated actively in the survey. This was sufficient to get reliable statistics (Table 2), and a good overview of the overall energy infrastructure on the island. However, the relatively low response rate does also indicate that the survey could have been made more user-friendly (e.g. more visually appealing). It could also serve as an indicator of the local community's engagement and interest in issues related to renewable energy and energy efficiency. A new survey should be made after the results from this report have been communicated to the public.

3.4 Summary

A synthesized hourly electricity power demand profile based on Figure 6 and Figure 7 was used in the wind/diesel system simulations described below, while a load profile resulting in twice the electricity demand was used in the wind/diesel/DHT-system simulations.

The space heating demand profile used in the wind/diesel/DHT-system simulations was derived from the estimated overall thermal energy demand (27000 kWh_{th}/year in total, hereof 4000 kWh_{th}/year for hot tap water) and the average monthly ambient temperatures at Nólsoy (the thermal load is an inverse sinusoidal function of the ambient temperature).

4 Wind Energy Potential

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 cause local wind patterns, and several locations such as Nólsoy, will be prone to 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 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 southwest. The wind speed is generally higher during the winter than the summer. Even though the general climate is very windy, calm periods can occur, most often during midsummer, but then only for very short periods of time [9].

In order to get an exact estimate for the wind energy potential at Nólsoy it was decided to install a 30 meter high mast and wind energy monitoring equipment at a representative site near the village. An inspection of the site at Nólsoy was made on 3 May 2006 (Figure 8). The visit included participants from the West Nordic project group, Kjeller Vindteknikk AS (wind monitoring specialists), and Røkt (a local wind energy entrepreneur). The preparation and planning of the wind monitoring project took a little less than a year, and on 10 March 2006 the first wind speed measurements were made at Nólsoy. Measurements are made at two different heights (20 and 30 meters) with 10-minute intervals. The wind data is automatically transmitted and uploaded to a web site at Risø National Laboratory in Denmark. A plot of the hourly averages wind speeds available for the first 3 months of the wind monitoring project is shown in Figure 9.

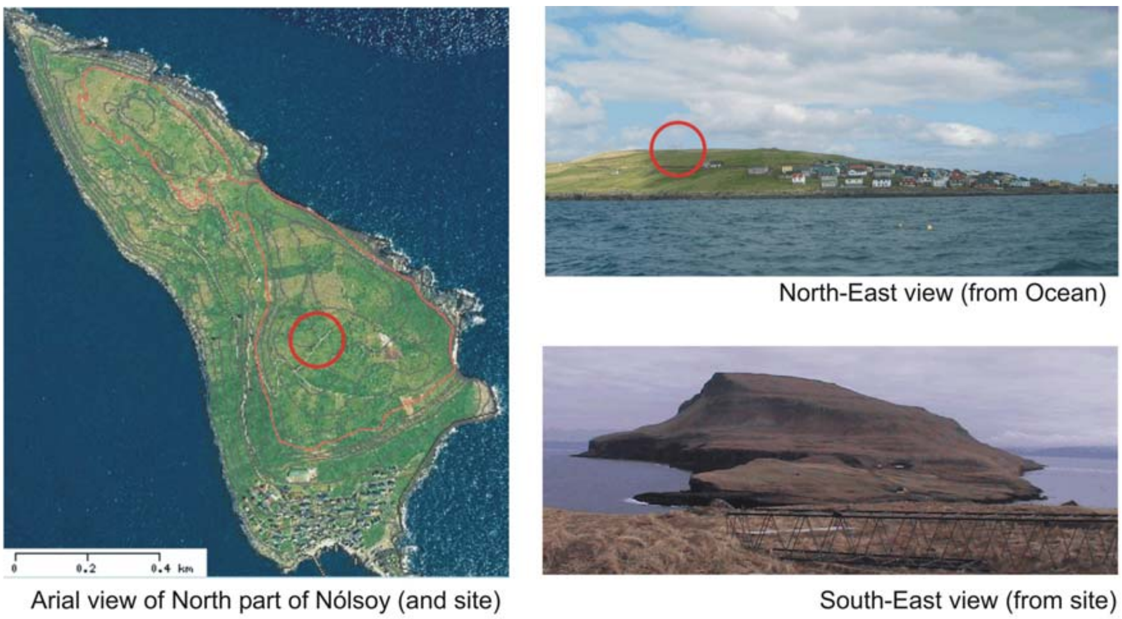

Figure 8 Overview of the site chosen for wind energy measurements at Nólsoy.

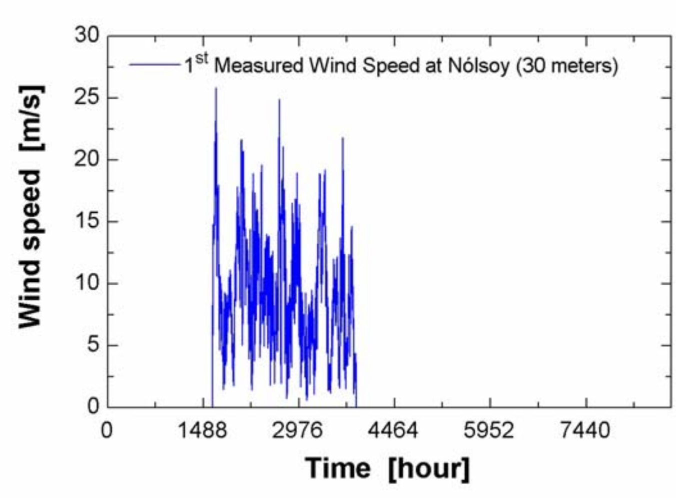

Figure 9 First period with wind speed measurements made at Nólsoy (10 March – 10 June 2006)

The first wind speed data measurement made at Nólsoy (Figure 9) was used to generate an hourly annual wind speed profile for the system simulations described below. This annual wind speed profile was synthesized in two steps. First, a simple linear wind speed correlation was found between the site at Nólsoy and a reference station at Mykines Fyr. The annual wind speed profile for the reference station (with long-term data available) was calculated in Phase I of the project [1]. Hence, a preliminary annual hourly wind speed profile for Nólsoy could be established. It should be noted that as soon as more data (preferably 12 months worth of data) is available, a more proper correlation [between site and reference station] and an estimation of the long-term wind energy potential for Nólsoy could be made.

5 System Analyses

This chapter summarizes the main results from the numerous system simulations and analyses undertaken in Phase II of the West Nordic project. It should be noted that the results reported here are tentative, and the final simulations will be performed towards the end of Phase III of the project, once more accurate time series for wind speeds and electricity demand can be established based on actual wind and power measurements at Nólsoy.

5.1 Simulation Modeling Tools

The modeling and system analysis performed within the West Nordic project is based on a transient system simulation program (TRNSYS) (http://sel.me.wisc.edu/trnsys). In Phase I of the project a set of hydrogen energy models (HYDROGEMS) was used to demonstrate the feasibility of integrating hydrogen energy systems into existing wind/diesel-based power systems in the West-Nordic region [1].

In Phase II of the project the focus has been more on developing specific thermal energy models. Thus, standard TRNSYS-components for domestic hot water tanks (DHTs) and special TRNSYS-libraries, including heat pump models from Thermal Energy Systems Specialists (www.tess-inc.com), were used in the simulations.

The HYDROGEMS-library is a collection of hydrogen energy models suitable for simulation of integrated hydrogen energy systems, particularly renewable energy systems (www.hydrogems.no). The models have been developed by IFE since 1995, and were made publicly available for TRNSYS version 15 in 2002 [8], and were officially adopted into TRNSYS version 16 in 2005 (http://sel.me.wisc.edu/trnsys). In the interim period (2002-2005) about 175 users were registered in 56 organizations in 20 countries, with ca. 50% of the users were from academia, 25% from research institutes, and 25% from commercial companies.

The following HYDROGEMS-models have been developed, tested, and verified in various projects at IFE over the past 10 years [10,11]: (1) Wind energy conversion systems (WECS) (2) Photovoltaic systems (PV), (3) Water electrolysis (advanced alkaline, but adaptable to PEM), (4) Fuel cells (PEM and alkaline), (5) Hydrogen gas storage, (6) Metal hydrides (MH), (7) Hydrogen compressor, (8) Secondary batteries (lead-acid), (9) Power conditioning equipment, and (10) Diesel engine generator systems (multi-fuels, including hydrogen).

A more detailed description (in Norwegian) of the previously established wind/diesel/hydrogen energy system simulation tools is found in the final report for Phase I of the project [1], while more details on the thermal energy system modeling, particularly the domestic hot water tank (DHT) modeling, is found in a related Masters study [4].

5.2 Reference System

A stand-alone diesel engine generator system was selected as the reference system (Figure 10) for the base case simulation studies performed.

Figure 10 Reference system.

An annual simulation of the reference system (Figure 10) based on the electricity demand profile for Nólsoy (Figure 6 and Figure 7) and a 250 kW diesel engine generator system yields and overall diesel fuel consumption of V_{diesel} = 210000 liters/year and an overall cost of energy of COE = 0.09 €/kWh$_{\text{el}}$.

The annual emissions from running the system entirely on diesel fuel is significant, but even just as importantly is the environmental costs and risks of transporting and storing the fuel locally (Figure 11) (210000 liters of diesel fuel is equal to ca. 1400 barrels).

The existing fuel storage capacity at Nólsoy is ca. 150000 liters, which means that a full refill of the storage would be required ca. every 8 months. This means that, from a logistical point of view, it is realistic to operate the DEGS power system in a stand-alone mode (i.e., independently of the main grid).

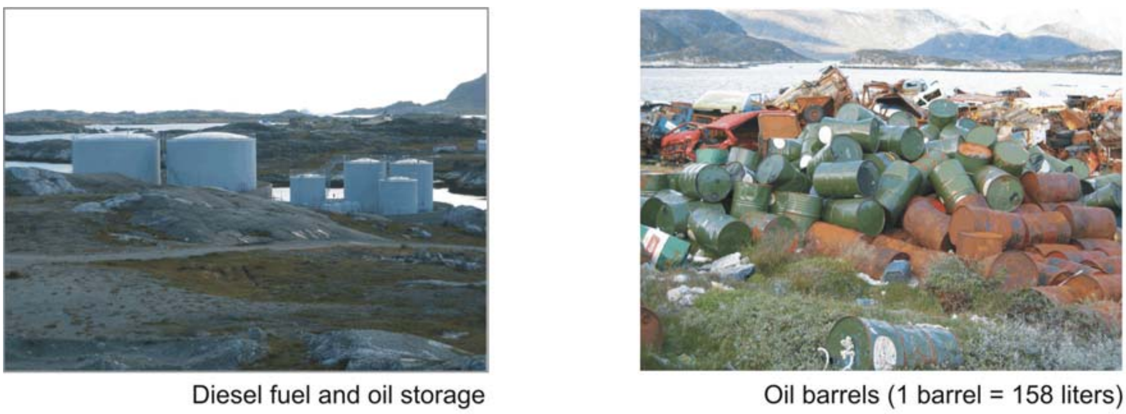

Figure 11 Diesel fuel and oil storage in Nanortalik, South Greenland (Photos: Ø. Ulleberg, 2005).

5.3 Wind/Diesel System

The first main alternative system considered in this study was a stand-alone wind/diesel power system configured to meet the total electrical demand (ca. 670 MWh/year) for the Nólsoy mini-grid (Figure 12). The main objective with this system concept is to displace as much diesel fuel as possible by using local wind energy available at Nólsoy.

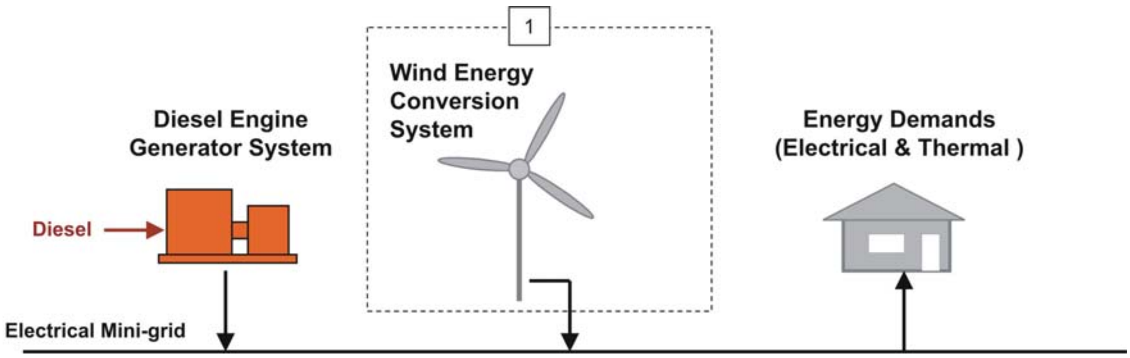

Figure 12 Wind/diesel power system.

Annual simulations of a wind/diesel system (Figure 12) based on the electricity demand profile for Nólsoy (Figure 6 and Figure 7) and a synthesized annual wind energy profile, based on 3-months wind data from Nólsoy (Figure 9), was performed for various system configurations. Table 3 summarizes the main results for the diesel only and wind/diesel system simulations performed.

The results (Table 3) show that a hybrid wind/diesel system with WECS power rating of 300 kW and a DEGS power rating of ca. 250 kW, gives a 40-55% reduction in diesel fuel consumption compared to the reference system, without increasing the cost of energy significantly. A design with 3 × 80 kW diesel generators is more optimal than a design with 2 × 125 kW generators, because it allows for more efficient overall operation of the diesel engine generator system. It should be noted that individual generators in the DEGS were allowed to idle down to 25% of their rated power, which is a fairly optimistic assumption. Nevertheless, a diesel fuel reduction of about 40% does not seem too unrealistic.

The optimal configuration (3 × 80 kW generators) gives an overall wind energy penetration (fraction of total load covered by wind energy) of around 50-60%, which is very high for a stand-alone wind/diesel power system. At the same time about 80% of the wind energy available from the WECS is being dumped. This means that the installed WECS is slightly oversized and much more of the wind energy could have been utilized. The possibility of converting some of the excess wind energy to heat through the use of distributed hot water tanks (DHTs) or heat pumps should therefore be considered as a near-term option. The production of hydrogen could be considered as a future option. All of this is investigated in more detail below.

Table 3 Comparison of key design parameters and corresponding main results for the Nólsoy diesel only (reference) and wind/diesel system simulations.

	DEGS only	**DEGS/WECS**		
	Reference	**Alternative 1**	**Alternative 2**	**Units**
Design Parameters:				
Rated DEGS power	2×125 = 250	2×125 = 250	3×80 = 240	kW
Rated WECS power	0	300	300	kW
Total electricity demand	677	677	677	MWh/year
Main Results:				
Energy from DEGS(1)	703	346	265	MWh/year
Potential energy from WECS	0	1 744	1 744	MWh/year
Part of load covered by WECS	0	49	62	%
Part of wind energy dumped	0	81	76	%
Diesel consumption	220 359	132 303	99 182	liters
Cost of energy	0.09	0.11	0.10	€/kWh

(1) The DEGS were allowed to idle down to 25% of their rated power, which means that they will have to dump some power during periods with very low electricity demand.

5.4 Wind/Diesel System with Distributed Domestic Hot Water Tanks

The second basic alternative system considered in this study was a wind/diesel system with distributed domestic hot water tanks (DHTs) for hot tap water and/or space heating (Figure 13). At Nólsoy almost all of the households have installed oil-fired hot water radiators (Table 2). This means that there exists an excellent opportunity to capture some of the excess wind energy in the form of hot tap water (60-90°C tanks) and/or space heating (80-90°C radiators).

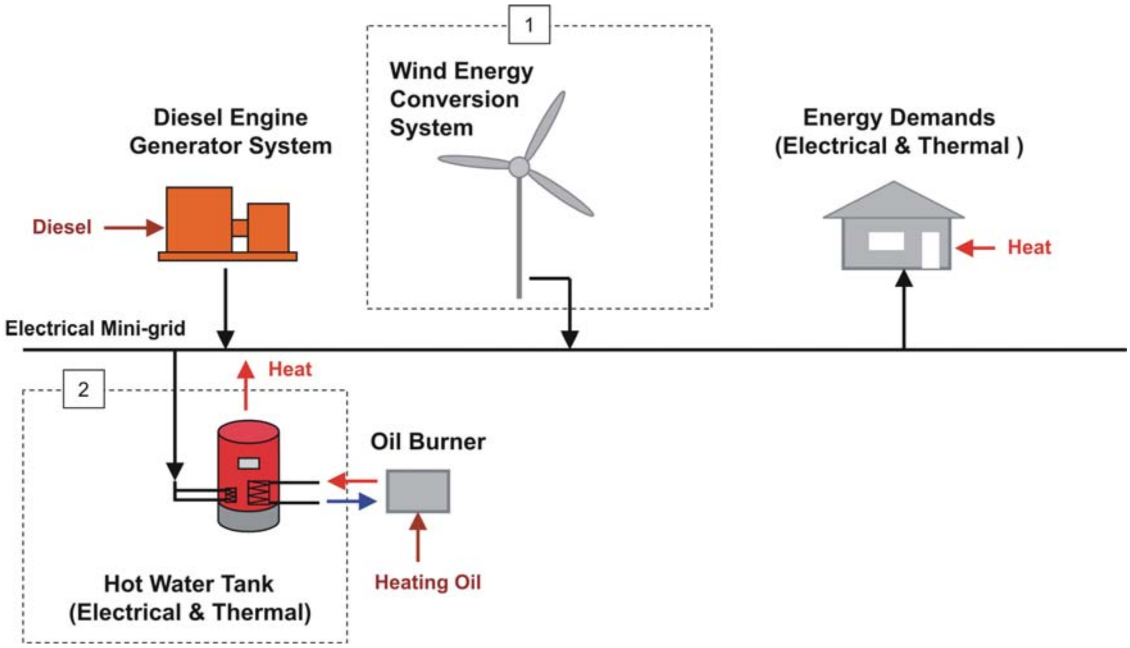

Figure 13 Wind/diesel energy system with distributed domestic hot water tanks.

It should be noted that heat pumps could also be used for tap water and space heating in the wind/diesel/DHT system configuration described above (Figure 13). Since the optimal coefficient of performance (*COP*) for heat pumps normally occur at low temperatures around 35-40°C, they are not well suited for the typical household at Nólsoy, which requires high-temperature heat (60-90°C) for their hot water tanks and radiators. However, heat pumps should be considered for new and more modern houses and buildings with low-temperature (35-40°C) floor heating systems.

5.4.1 DHT Technology & Control Issues

Two main assumptions need to be made for the system configuration described in Figure 13. The first assumption is that the electrical (resistive) heaters in the DHTs can be switched on/off by a signal sent from a master control system. This means that some kind of communication between the master control system and the individual DHTs must be possible. The second assumption is that there exist suitable multi-source (thermal/electrical) DHTs on the market that can be used with the existing oil burners.

The most common communication techniques fall into the following categories: Wireless radio, power line carrier, cable, fiber optics, and telephone line. In practice, there are only two suitable options for the power system at Nólsoy:

1. Wireless radio

2. Power line carrier

At Nólsoy the power system is connected to the same low-voltage grid, and no ripple signals 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. Nólsoy has currently a central wireless network transmitter that offers a high-speed Internet connection. Thus, it can be concluded that a relatively simple and inexpensive load control system for the DHTs can be installed at Nólsoy.

A brief survey on the DHT-technology itself shows that there are several commercial multi-source (electrical/thermal) DHTs available on the market. A modern multi-source DHT, such as the one shown in Figure 14, is typically equipped with a 3-6 kW_{el} (60-90°C thermostat) electrical heating element and a 26 kW_{th} (at ΔT = 20 °C) thermal heat exchanger, comes in sizes of 150, 200, and 300 liters, and costs ca. 1000 €.

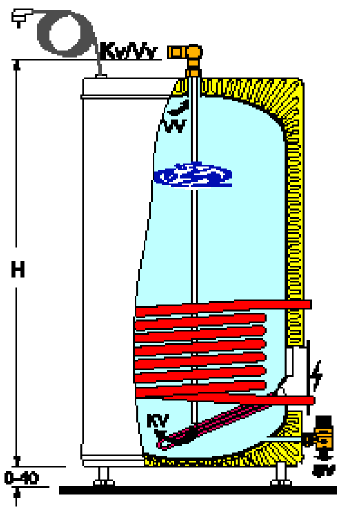

Figure 14 Multi-source domestic hot water tank (Source: www.oso.no)

In practice, the individual DHTs in a wind/diesel/DHT-system (Figure 13) must be regulated so that the excess wind power is dumped into the storage tank via the electrical heating element when the temperature in the tank is in the range 60-90°C. If there is no excess wind power available and the temperature in the tank falls below 60°C, the oil burner must start up and heat the tank until sufficient excess wind energy is available. Normally, temperature dead bands (typically ΔT = 5°C) will be built into the system to prevent too frequent on/off-switching of the heaters, in this case the oil burner. The last point assumes that the existing oil-burners can be used to heat the hot fluid going into the DHTs, and that this can be done in an automatic manner (e.g., thermostat regulated).

5.4.2 Results from Detailed DHT System Simulations

Detailed simulations studies of various wind/diesel/DHT-system configurations (Figure 13) have been performed in a related Masters study [4], and only the main technical conclusions from this study are included in this report. More detailed cost calculations on the most interesting system configurations should be carried out in Phase III of project.

The main inputs, key design parameters, and main results from the detailed wind/diesel/DHT-system simulations performed in [4] are summarized in Table 4. Again, it should be noted that the overall electricity demand (Table 4) was twice as high as that assumed in the other simulations performed in this study (Table 3). This means that the results from the Masters study must be treated independently from the rest of this study.

In the simulation of the wind/diesel/DHT-systems tap water configuration (Table 4, Alternative 1) it was assumed that the excess wind energy was distributed evenly among the DHTs. Four hot water tanks with various volumetric sizes and electrical heating element capacities (kW) were to simulate the overall thermal behavior of the hot water storage system. The results were then extrapolated to 100 households (i.e., multiplied by 25) in order to get the overall system performance. With this approach it was possible to study the thermal dynamic behavior of the individual DHTs, and evaluate the technical feasibility of storing excess wind power as heat in distributed DHTs.

In order evaluate the simulation results for the two alternative types of wind/diesel/DHT-systems configurations (tap water only or space heating with radiators), three different reference systems were established:

1. A hybrid wind/diesel power system designed to meet the electricity demand (265 kW_{peak}, 1 366 000 MWh_{el}/year ; refer to Table 4 for further specifications)

2. A fuel oil based hot tap water system (3794 kWh_{th}/year per household)

3. A fuel oil based radiator heating system (28125 kWh_{th}/year per household)

A closer look at the first alternative (DHT for tap water only) shows that it is possible for a wind/diesel/DHT system to cover about 75% of the total hot tap water demand, provided there is a significant amount of excess wind energy available in the system. (This was assured by over-sizing the WECS). In general, the overall heat losses in DHTs increase with increasing tank volume. The simulations showed that an individual tank with a volume of about 1000 liters seems to be optimal. In the simulations it was assumed that each DHT had one single electrical heating element that could only be switched on/off. The optimal power capacity on this electrical heating element turned out to be about 1000 W. In an actual system one could consider using several heating elements in a single DHT, but this could complicate the system controls, particularly if all 100 households at Nólsoy were to be connected to a single master control system. Nevertheless, the results show that a significant amount off heating oil (310 liters/year per household) can be displaced by wind energy at an acceptable cost of energy[1] (0.075 €/kWh_{th}).

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[1] The cost of energy is only based on approximate investment costs for the DHT-system (including control system), and does not include the extra investment costs associated with the increased wind power capacity.

A similar analysis on another heating alternative (DHT for space heating) shows that, with the same system constraints (same electrical load, diesel engine gen set, wind turbine), it is possible to cover about 25% of the space heating demand with excess wind energy. It turned out that the optimal tank volume for each individual DHT was about 50 liters, while the best power rating on the electrical heating element was 1500 W. The reduction in the heating oil consumption (776 liter/year per household) for the DHT space-heating system was greater than the reduction achieved with a DHT tap water system (310 liters/year per household). This means that a DHT space heating system is able to utilize more wind energy than a DHT tap water system. The cost of energy for a DHT space heating system was estimated to be (0.030 €/kWh_{th}), which also is lower than the cost of energy for a tap water system. In comparison, fuel oil is currently priced at ca. 0.080 €/kWh_{th}.

Table 4 Summary of main inputs, key design parameters, and corresponding main results for the Nólsoy wind/diesel/DHT system simulations [4].

	WECS/DEGS	**WECS/DEGS/DHT**		
	Reference	**Alternative 1: Tap Water**	**Alternative 2: Space Heat**	**Units**
Main Inputs:				
Total electricity demand	1 366 000	1 366 000	1 366 000	MWh/year
Tap water per household (2)	N/A (1)	3 794	N/A	kWh/year
Space heating per household (2)	N/A	N/A	28 125	kWh/year
Design Parameters:				
Rated DEGS power	300	500	500	kW
Rated WECS power	300	800	800	kW
Volume of individual DHT	N/A	1 000	50	liters
Power rating in individual DHT	N/A	1 000	1 500	W
Main Results:				
Energy from DEGS	587	489	489	MWh/year
Potential energy from WECS	1 744	4 281	4 281	MWh/year
Tap water covered by WECS	N/A	75	N/A	%
Space heating covered by WECS	N/A	N/A	25	%
Total diesel consumption	421 780	161 180	161 180	liters
Total reduction in fuel oil	N/A	31 023	77 668	liters
Cost of energy (3)	0	0.075	0.03	€/kWh_{th}

(1) Not Applicable
(2) 100 households assumed
(3) Only based on DHT investment costs, no extra wind energy systems costs included

5.4.3 DHT System Conclusions and Recommendations

The main conclusion from the technology evaluations and detailed thermal energy system simulations above is that it makes sense to design a power mini-grid with a slightly over-sized wind energy conversion system, and convert some of the excess wind energy into thermal energy via electrical heating elements in distributed DHTs (Figure 13).

At Nólsoy, where there exists a domestic infrastructure with hot water radiators, it seems most logical to design the distributed domestic hot water tanks for space heating. However, in order to have the possibility to meet a large portion of the hot tap water demand with wind energy, the installation of a large tank (300-1000 liters) is also recommended.

The cost calculations performed above are rough estimations, and should include the extra investment costs associated with increasing the power capacity of the wind turbine. However, it does not make sense to perform more detailed cost calculations before the final wind energy profile (based on ongoing wind speed measurements) and a more detailed electrical demand profile is available.

5.5 Heat Pump System (Case Study 1)

The feasibility of attaching a heat pump system to a wind/diesel mini-grid (Figure 15) so that it can meet the space heating demand for a larger building in Nólsoy was investigated in a separate case study.

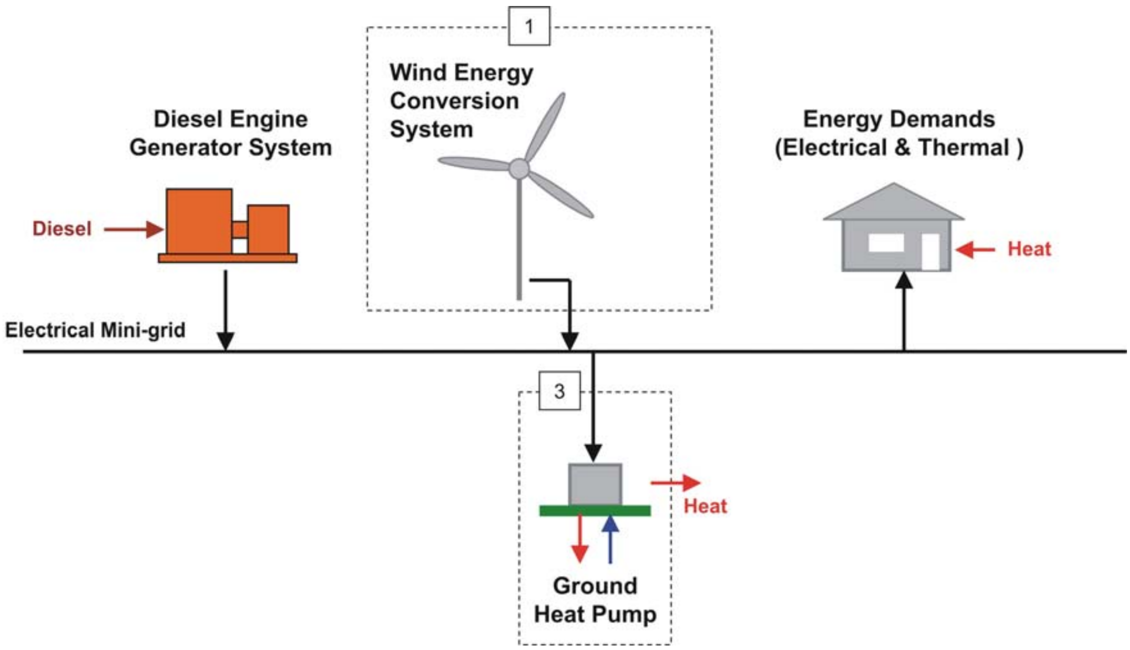

Figure 15 Wind/diesel/heat pump system.

5.5.1 Heat Pump Technology Issues

The energy survey at Nólsoy demonstrated that most of the households use oil burners and water based radiator systems designed for temperatures around 60-80°C. Technically, it is difficult to integrate a low-temperature (30-40°C) heat pump into such a system. This is because the existing radiators will not be able to deliver the required amount of heat flux at so low temperatures. A high-temperature (60-70°C) heat pump could be used, but in order to get an acceptable efficiency, or coefficient of performance (*COP*), this would require access to a heat sink with a fairly high temperature (15-20°C). This is explained by Figure 16, which shows the typical relationship between *COP* and temperature rise (i.e., temperature difference between the inlet (heat sink) and outlet).

At Nólsoy one could possibly use sea water as the heat sink (5-20°C) for a large heat pump system located close to the quay. However, this would only make sense if the heat could be distributed to a large user located nearby. Another possibility is to drill a borehole and install a ground heat pump system for a dedicated user with a demand for high quality indoors climate and comfortable low-temperature space heating, such as a childcare center. This is exactly what is proposed for Nólsoy. A schematic of the proposed system concept is shown in Figure 17.

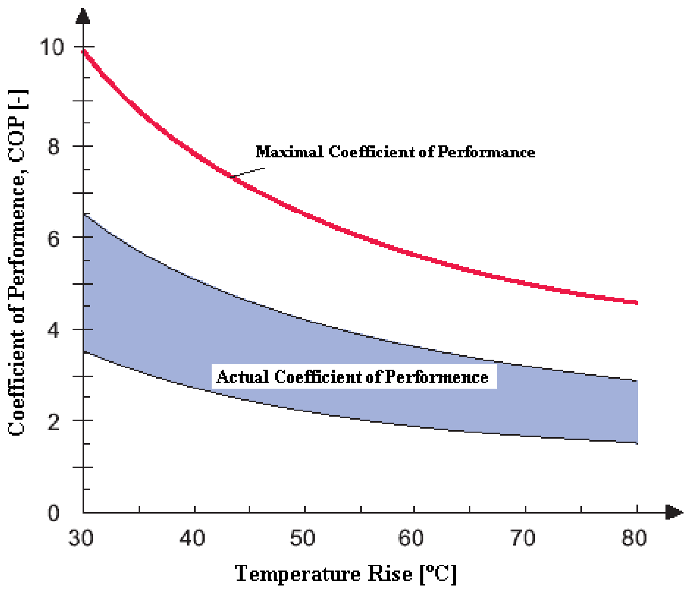

Figure 16 Heat pump characteristics; coefficient of performance (COP) vs. temperature rise (ΔT) [12].

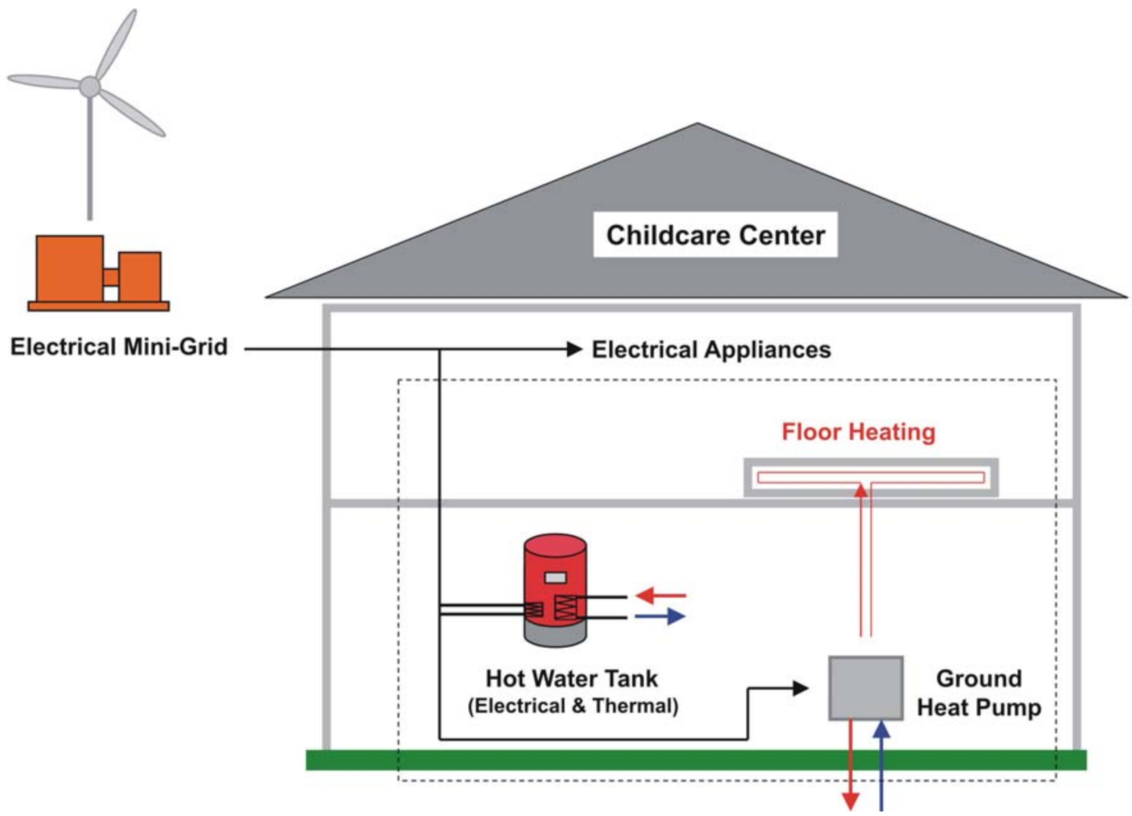

Figure 17 Heat pump system (boundary shown by dotted lines) proposed for childcare center at Nólsoy.

5.5.2 Results from Heat Pump System Simulations

The design of the heat pump/floor heating system shown in Figure 17 (system boundary indicated by dotted lines) was investigated and simulated in detail in this study. A summary of the main system design, assumptions, and corresponding results for the heat pump system simulations is provided in Table 5.

Table 5 Summary of main inputs, key design parameters, and corresponding main results for the Nólsoy heat pump system simulations (Case study 1)

Item	**Specification**	**Comments & Assumptions**
Main Inputs:		
Specific thermal energy demand	40 W/m² [12]	*U*-values for new homes assumed [13]
Heat demand in coldest month	3.26 MWh	Lowest temperature (3.6°C) in January (1)
Design Parameters:		
Type of heat pump system	Water to water	Constant ground heat at 4°C
Rated power	5 + 1 = 6 kW	Heat pump + water pumps
Volume DHT-system	1000 liters	Well-insulated, heat losses included
Net heated floor area	100 m²	Pressure losses in water tubes neglected
Floor temperature	30-40°C	Heat losses in feed water pipes neglected
Main Results:		
Maximum monthly average COP	3.6	Based on heat demand for January
Monthly electricity demand	1.34 MWh	Heat pump + water pumps

(1) Based on statistical data from Mykines Fyr [1]

The heat pump system simulation gave an average coefficient of performance *COP* = 3.6, which is very high. The climate on the Faroe Islands is temperate, and the average monthly temperature typically varies from 3.6°C in January (coldest month) to 9.6°C in August (warmest month) [1]. Since the variation in ambient temperature over the year is so small, the corresponding space heating demand profile will be quite smooth. This means that it will be possible to design a highly energy efficient heat pump system at Nólsoy with a yearly average coefficient of performance close to *COP* = 3.5. In comparison, a similar system located in a colder climate (e.g. Nanortalik, South Greenland) is not likely to achieve the same high overall average *COP*.

The rated power for the overall heat pump system (heat pump compressor and water circulation pumps) described above (Table 5) is ca. 6 kW. This is relatively small compared to the overall power available in the system, which has an overall maximum power rating greater than 250 kW (WECS + DEGS). Thus, a dedicated heat pump, such as the one proposed above (Figure 17), should easily be handled by a stand-alone hybrid wind/diesel mini-grid power system (Figure 15).

5.5.3 Heat Pump System Conclusions & Recommendations

On the Faroe Island in general, and at Nólsoy specifically, air-to-air heat pumps might be a viable alternative to water-to-water heat pump. This is particularly true if the air-to-air heat pump can be used for space heating in individual homes. At Nólsoy an air-to-air heat pump could possibly replace or supplement the existing radiator-based domestic space heating systems on the island. However, it should be noted that air-to-air heat pumps have been reported to have some corrosion problems in coastal areas with salty moist air (due to ocean spray). This problem cannot be neglected at Nólsoy.

A simple economic comparison between water-to-water and air-to-air heat pumps based on an annual space heating demand of 30000 kWh/year (approximate demand for a dwelling at Nólsoy) is provided in Table 6. If one assumes a general electricity price of 0.12 €/kWh_{el} (typical price for the Faroe Islands), which also is comparable to the *COE* calculated for the electrical systems considered for Nólsoy (Table 3), the cost of energy for the heat pump systems is around ca. 0.06 €/kWh_{th}. This is competitive to the *COE* calculated for the wind/diesel/DHT-systems (Table 4) and the current price of fuel oil (0.08 €/kWh_{th}). In summary, a water-to-water heat pump system for the childcare center seems to be a technically and economically viable solution for Nólsoy.

Table 6 Economic comparison between typical water-to-water and air-to-air heat pumps.

	Type of Heat Pump		Units
	Water-to-Water	Air-to-Air	
Design Parameters:			
Annual space heating demand (1)	30 000	30 000	kWh_{th}/year
Maximum space heating demand	6	6	kW_{el}
Economic Parameters:			
Heat pump investment cost (2)	1020	500	€/kW_{th}
Heat pump life time	20	10	years
Floor heating investment cost	35	0	€/m^2
Electricity price (3)	0.12	0.12	€/kWh_{el}
Total system life time	25	25	years
Operating & maintenance cost	3	3	%
Interest rate	6	6	%
Overall Costs:			
Annualized system cost	1 674	1 600	€/year
Cost of energy	0.062	0.056	€/kWh_{th}

(1) Estimations for Nólsoy made in this study

(2) Estimated cost based on brief survey among heat pump suppliers in the Nordic countries

(3) Average electricity price for the Faroe Islands (Source: SEV)

5.6 Hydrogen Storage and Dispenser System (Case Study 2)

The concept of integrating a hydrogen energy storage and dispenser system that can capture and utilize some of the excess wind energy available in a wind/diesel mini-grid system (Figure 18) on Nólsoy is discussed below. Detailed simulation studies of this concept can only be made when complete wind speed and electricity demand profiles have been established. Thus, only a few example calculations are reported in this study.

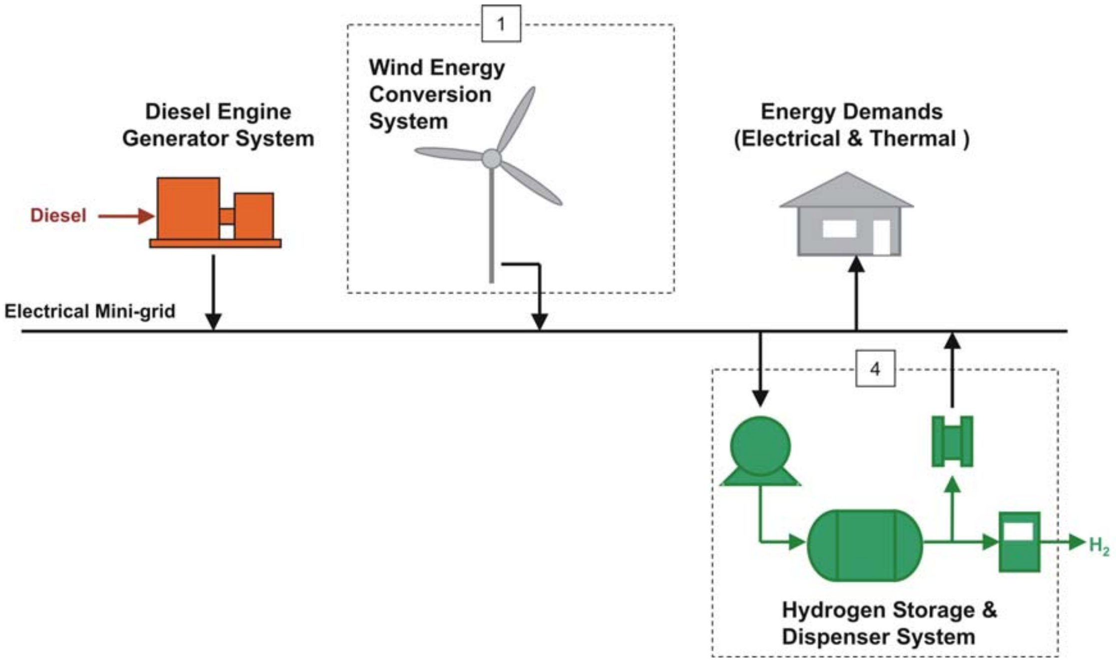

Figure 18 Wind/diesel/hydrogen system.

5.6.1 Basic Hydrogen Storage and Dispenser System Concept

The basic idea behind the hydrogen storage and dispenser system shown in Figure 18 is to maximize the use of the installed electrolyzer hydrogen production capacity and at the same time to try to minimize the need for a large hydrogen storage. This can only be achieved through a carefully designed system that balances the hydrogen produced by the electrolyzer with the hydrogen demand [11]. In practice, this means that it is necessary to identify a number of possible hydrogen end-users, both for stationary and transport applications (e.g., UPS for telecom, scooters, electrical vehicles, boats, ferries).

At Nólsoy there is a passenger ferry that frequently crosses over to Tórshavn (ca. 20 minute boat trip). The diesel engine for this ferry is relatively large (ca. 200 kW). Based on the current cost of the fuel cell technology (e.g. a 200 kW PEM fuel cell system from Ballard, Canada) it is not economically realistic to replace the diesel engine with a hydrogen fuel cell. A hydrogen-based internal combustion engine (ICE) could be considered, but because of its relatively poor energy efficiency (ca. 15%), excessively large hydrogen storage would be required. Furthermore, since the ferry only stops briefly in Nólsoy, before it returns to Tórshavn, the need for a large hydrogen storage is even further increased.

The conclusion from the above is that it is not realistic to replace the ferry's existing diesel engine with a hydrogen based internal combustion engine or fuel cell system, using the existing hydrogen technology available on the market today. However, there exist two alternative approaches that may be realistic:

- **Ferry Alternative 1:** A new lightweight (aluminum) ferry that requires less power and less fuel could be installed. Because of the short distance between Nólsoy and Tórshavn it should be possible to design and build a smaller hydrogen fuel cell (or H_2-ICE) driven passenger boat that meets the transportation for the islanders at Nólsoy. The disadvantage with this alternative is that the fuel cell ferry would rely 100% on the available wind energy, which could lead to the need of a very large hydrogen storage at the site of the dispenser.

- **Ferry Alternative 2:** A gas engine that operates on mixtures of natural gas and hydrogen (8-25% volumetric hydrogen [14]) could replace the diesel engine in the existing ferry. The advantage with this alternative is the possibility to operate the ferry on pure natural gas or lean mixtures when there is little hydrogen available in the storage tank at the site of the dispenser. The disadvantage with this alternative is that a completely new gas engine must be retrofitted to the ferry. Furthermore, there needs to be a natural gas hydrogen dispenser present on Nólsoy, which might cause some logistical challenges.

Alternative 2 is only partially based on renewable energy, and can therefore only be viewed as a possible transition technology towards 100% clean transportation. The main drawback with this alternative for Nólsoy is that there exists no natural gas infrastructure on the island. Hence, Alternative 1 seems to be the most interesting option, even though it requires some further technology development, both on the boat itself (novel light-weight design) and on the propulsion system (fuel cell and electric motor).

5.6.2 Example Calculations for Wind/Diesel/Hydrogen Storage System

The purpose with the simple example calculations presented below is to provide a rough estimate of the hydrogen produced in a small (10 Nm^3/h) electrolyzer located by a dispenser at the quay, and connected to the wind/diesel mini-grid at Nólsoy (Figure 18).

In general, the electrolyzer should only operate during periods with excess wind energy (i.e., diesel generators should not power the electrolyzer), as hydrogen based on 100% on renewable energy is the main justification for the entire concept.

If one assumes that a small lightweight hydrogen ferry requires a 100 kW fuel cell (a smaller fuel cell could be run in parallel with batteries) and that the ferry operates continuously for one hour (round-trip Nólsoy-Tórshavn-Nólsoy) before it is refilled, the hourly hydrogen demand in the fuel cell can be estimated from the simplified equation:

$$V_{H2,FC\text{-ferry}} = 100 \text{ [kW]} / 1.75 \text{ [kWh/ Nm}^3\text{]} \times 1 \text{ [hour]} = 57.1 \text{ Nm}^3 \qquad \textit{Equation 1}$$

which assumes that the fuel cell operates at constant power (100 kW) at an efficiency of 50 %, which yields a specific energy consumption of about 1.75 kWh/Nm^3. If one assumes three round-trips between Nólsoy-Tórshavn per day, the total daily hydrogen demand for the ferry would be about 170 Nm^3/day, or about 7 Nm^3/hour on average.

Next, a simple simulation of a wind/diesel/electrolyzer/hydrogen storage system was made, based on the excess power available in the wind/diesel system described above (Figure 12 and Table 3). A standard electrolyzer with a hydrogen production capacity of 10 Nm^3/h and average specific energy consumption of 5.5 kWh/Nm^3 was assumed. No sophisticated electrolyzer system control was built into the simulations, except the fact that the electrolyzer was only allowed to operate from 40 to 100% of its rated capacity. This is valid for fairly standard alkaline electrolyzer technology, while PEM-based electrolyzers potentially can go down to 5-10 % of their rated power.

The main results from the wind/diesel/hydrogen system simulation is provided in Figure 19, which shows that a large hydrogen storage with a total capacity of 4000 Nm^3 is required in order to keep the hydrogen energy balance over the year. In comparison, the hydrogen storage at Utica (Figure 4) had a capacity of about 2400 Nm^3.

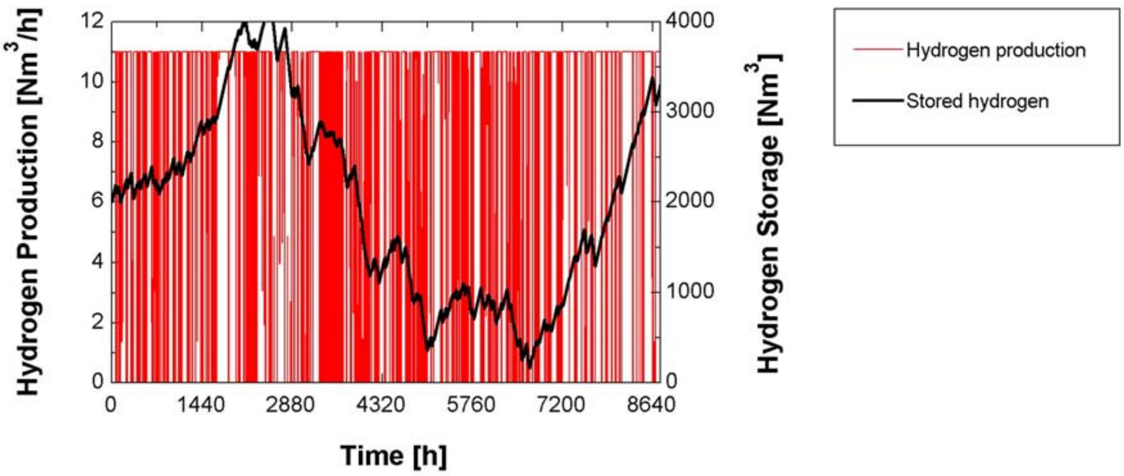

Figure 19 Hydrogen production and storage in a possible hydrogen system located in a wind/diesel mini-grid at Nólsoy.

The results above indicate that it is both theoretically and practically possible to build hydrogen storage system at Nólsoy that can deliver 100% renewable energy based hydrogen all-year round. The next step is to investigate possible designs for a hydrogen fuel cell ferry. The power rating of the fuel cell could, for example, be reduced if it runs in parallel with a battery. Furthermore, a technical solution that meets the requirement for on-board hydrogen storage (57 Nm^3 per round-trip) and hydrogen refueling (typically 10-15 minutes per filling for high pressure gaseous system) must also be found. Finally, it is necessary to determine if it is practically possible to build a hydrogen fuel cell based lightweight passenger ferry and put it in traffic between Nólsoy and Tórshavn.

6 Conclusions & Recommendations

The objective with the technical system analyses carried out in Phase II of West Nordic project was to propose and evaluate renewable energy system concepts suitable for the island of Nólsoy at the Faroe Islands. The method used was to:

1. Estimate the wind energy potential at Nólsoy.

2. Determine the electrical and thermal energy demands at Nólsoy based on statistical data from the local power company, oil suppliers, and a local energy survey performed on the island in 2006.

3. Compare the cost-effectiveness of wind/diesel generator system mini-grid configurations to existing diesel-only configurations.

4. Study in detail the technical feasibility of storing excess wind energy in distributed domestic hot water tanks (DHTs) for tap water and space heating.

5. Evaluate the technical and economical potential for installing alternative heat pump systems.

6. Evaluate the possibility of integrating a hydrogen energy system into a future stand-alone wind/diesel mini-grid system at Nólsoy.

The following conclusions can be made from Phase II of the project:

1. Wind speed measurements (at 20 and 30 meters and 10 minute intervals) began at Nólsoy on 10 March 2006. This data was used to generate a preliminary annual hourly wind speed profile for Nólsoy.

2. An energy survey at Nólsoy showed that the average tap water and space heating demand for a typical household (single dwelling from 1957 with 2.7 persons) is approximately 4000 kWh_{th}/year and 27000 kWh_{th}/year, respectively. The existing domestic heating systems typically consist of a fuel oil burner (20 kW_{th}), a hot water tank (180 liters), and high-temperature (60-80°C) radiators. The average electricity consumption per household is about 3700 kWh_{el}/year. The total electricity consumption at the island is about 670 MWh_{el}/year.

3. In a wind/diesel system, where the wind turbine has about the same power capacity (300 kW) as the diesel engine generator system (250 kW), an overall wind energy penetration of around 50-60% can be achieved, even though a large portion (80%) of excess wind energy must be dumped. This system configuration yields a diesel fuel reduction of about 40%, and an overall cost of energy of about 0.10 €/kWh_{el}.

4. A wind/diesel system with distributed domestic hot water heaters (DHTs) appears to be a technical and economical feasible option for most of the households at Nólsoy. Since there exist an infrastructure with radiators, DHTs with a capacity (300-1000 liters) suitable both tap water and space heating is recommended. The estimated cost of energy for such a DHT-system is 0.030-0.075 €/kWh_{th}.

5. A dedicated water-to-water (ground heat) heat pump coupled to a low-temperature (30-40°C) floor heating system (100 m^2) is recommended as an alternative option for space heating of the childcare center at Nólsoy. The cost of energy for the proposed heat pump systems is around 0.06 €/kWh_{th}, which is competitive to the current price of heating oil (0.08 €/kWh_{th}).

6. Preliminary results show that a relatively small (10 Nm^3/hour or 55 kW) electrolyzer system that only runs on excess wind energy could meet the hydrogen demand for a light-weight hydrogen fuel cell (100 kW) passenger ferry with three daily round-trips between Nólsoy and Tórshavn. However, a 100% renewable energy option would require a fairly large (4000 Nm^3) hydrogen storage located by the dispenser at the quay in Nólsoy.

The following recommendations can made for future work for Phase III of the project:

- Complete wind speed measurements at Nólsoy, correlate the full time series (12 months with hourly data) with a reference stations (Mykines Fyr), and estimate the long-term wind energy potential at the island.

- Monitor the electricity consumption (current and voltage) on the existing mini-grid at Nólsoy at high resolution (1-60 minute time intervals) for a longer period of time (1-3 months if possible) so that a more detailed power demand profile can be created for more accurate system simulations.

- Re-run the most interesting wind/diesel system (electrical) and wind/diesel/DHT system (electrical and thermal) simulations based on longer and more detailed wind speed and electricity consumption time series

- Plan an actual project at Nólsoy in the following order (6 project stages):

    1. Perform energy efficiency.
    2. Install a diesel engine generator system suitable for stand-alone operation.
    3. Install a wind energy conversion system with a sophisticated control system.
    4. Install controllable distributed domestic hot water tanks in households
    5. Install a ground heat pump floor heating system at the childcare center.
    6. Build a hydrogen storage and dispenser system capable of meeting the hydrogen demand for a lightweight hydrogen fuel cell passenger ferry.

- Establish project partners for different project stages:

    1. Project stages 1-4 (near term): Local community, system suppliers
    2. Project stage 5 (medium term): National organizations (financial incentives)
    3. Project stage 6 (long term): Nordic and EU-partners (research and demonstration)

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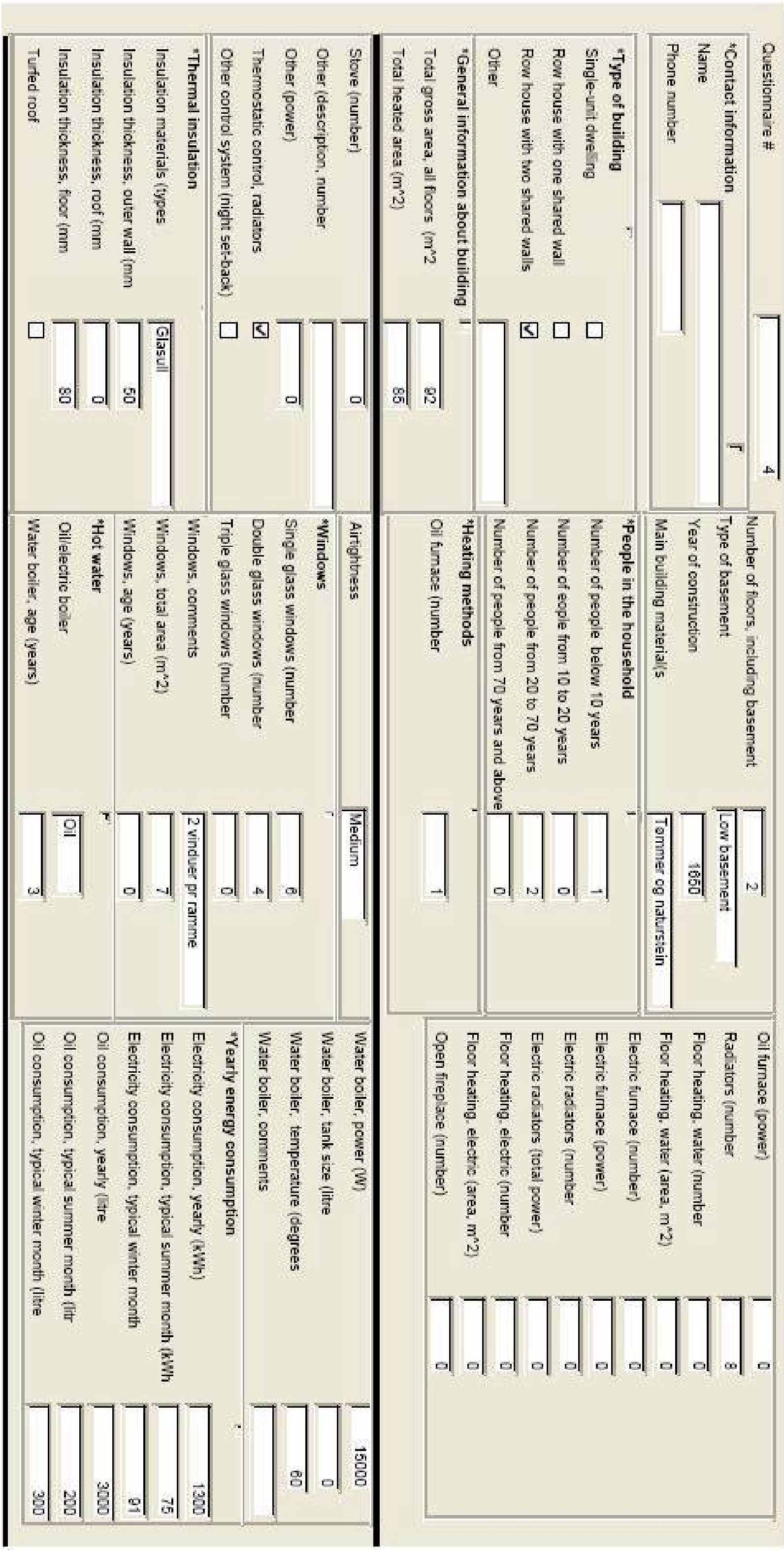
Appendix

Front-view of the database developed for energy survey performed at Nólsoy, May 2006.



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
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	☐

Number of floors, including basement	2
Type of basement	Low basement
Year of construction	1860
Main building material/s	Tommer 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
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

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
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

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