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# RENEWABLE ENERGY AND HYDROGEN SYSTEM CONCEPTS FOR REMOTE COMMUNITIES IN THE WEST NORDIC REGION – THE NÓLSOY CASE STUDY

Institute for Energy Technology

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**Abstract**

In 2003 the Nordic Council of Ministers granted the funding for the first of several studies on renewable energy and hydrogen (RE/H2) energy systems for remote communities in the West Nordic region. The objective with this report is to summarize the main findings from Phase II and III of the West Nordic project. The island Nólsoy, Faroe Islands, was selected as a case study. The following work was performed:

(1) Monitoring of wind and estimation of wind energy potential at Nólsoy.
(2) Measurement of actual power consumption and estimation of thermal energy demand based on statistics and energy survey at Nólsoy.
(3) Studies on wind energy utilization, system performance, and cost-effectiveness of wind/diesel-systems, with or without thermal storage.
(4) Studies on technical feasibility of storing excess wind energy in large centralized or small distributed hot water storage systems.
(5) Evaluation of techno-economic potential for a heat pump system.
(6) Evaluation of techno-economic potential for an on-site hydrogen production system suitable for a local passenger ferry at Nólsoy.

The main conclusion is that it makes sense to design a wind/diesel-system with thermal storage, both from a techno-economical and environmental point of view. Such systems can have close to 100% local utilization of the wind energy, and can cover up to 75% of the total annual electricity demand and 35% of the annual heat demand at a cost of energy around 0.07 - 0.09 €/kWh. The introduction of a hydrogen system is technically feasible, but doubles the overall investment costs.



**Keywords:** Renewable energy; autonomous energy systems; energy efficiency; wind/diesel power; thermal energy storage; on-site hydrogen production; techno-economic analysis


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## List of Acronyms

| Acronym | Description |
|---|---|
| AC | Alternating Current |
| COE | Cost of Energy |
| COP | Coefficient of Performance (for heat pumps) |
| DEGS | Diesel Engine Generator System |
| DHT | Domestic Hot Water Tank (often referred to as DHWT) |
| DIT | District Heating System (with centralized thermal storage tank) |
| DMI | The Danish Meteorological Institute |
| ECON | Economic and energy consultant company |
| EU | European Union |
| $H_2$ | Hydrogen |
| HP | Heat Pump |
| HYDROGEMS | Hydrogen energy models library |
| ICE | Internal Combustion Engine |
| IFE | Institute for Energy Technology |
| JTI | Joint Technology Intitiativ (EU) |
| NER | Nordic Energy Research |
| NTNU | Norwegian University of Science and Technology |
| PEM | Proton Exchange Membrane (as in PEM fuel cells) |
| PV | Photovoltaic |
| RD&D | Research, Development & Demonstration |
| RE | Renewable Energy |
| SEV | Local power company at the Faroe Islands |
| TRNSYS | Transient system simulation program |
| UPS | Uninterrupted Power Supply |
| WECS | Wind Energy Conversion System |

# 1 Introduction

In 2002 there was a meeting in the Council of Nordic Ministers in Haugesund, Norway. One of the topics discussed was on energy issues, and it was decided that there should be more focus on areas outside the Nordic power grid. As a result the Nordic Energy Committee and Nordic Energy Research were asked to perform studies on remote areas.

In 2003 Nordic Energy Research, ECON (Denmark) and Institute for Energy Technology (Norway) took an initiative towards the establishment of community-based renewable energy and hydrogen (RE/$H_2$) systems in the West Nordic Region.

In 2004 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 renewable energy system concepts developed and evaluated within the West Nordic project have evolved over time. The feasibility study in Phase I of the project marked the beginning of a series of system analyses and technical simulation studies performed at Institute for Energy Technology (IFE). Detailed system analyses were performed within Phase II and III of the project, as more detailed data became available (Table 1).

Two specific locations in the West Nordic region turned out to be the most interesting alternatives to follow-up: (1) Nólsoy, the Faroe Islands and (2) Nanortalik, South Greenland (Figure 1). The Faroese have shown great interest for the West Nordic project; they have co-funded the work, organized meetings, and made data available. Nólsoy was therefore used as a case study throughout Phase II and III of the project.

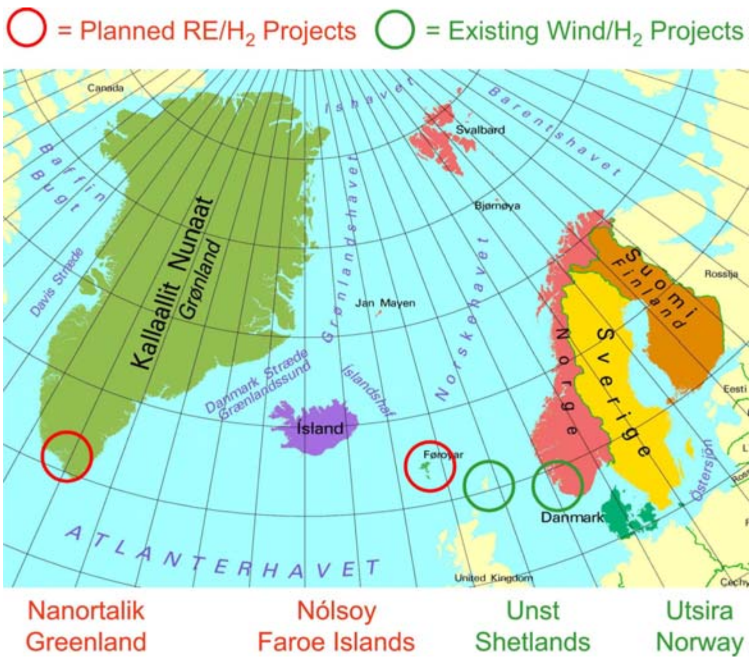


*Figure 1 Overview of existing and proposed renewable energy and hydrogen system (RE/$H_2$) demonstration projects in the West Nordic Region.*

*Table 1 Overview of the development in the West Nordic Project (2004-2007).*

| Phase | Period | Project Tasks |
|---|---|---|
| *I* | *2004 – 2005* | *Feasibility Study*<br>• Mapping of renewable energy and energy demand<br>• Identification of suitable sites for demonstration projects<br>• System concept development |
| *II* | *2005 – 2006* | *Definition and Evaluation of System Concept*<br>• Wind energy monitoring (Nólsoy)<br>• Energy survey<br>• Techno-economic case studies |
| *III* | *2006 – 2007* | *Verification of Specific System Concepts*<br>• Wind energy monitoring (Nanortalik)<br>• Detailed technical simulation studies |

## 1.1 Objective

The main objective with the work described in this report is to evaluate the various renewable energy and hydrogen system concepts considered for the island of Nólsoy at the Faroe Islands. The method and tools developed can readily be applied to similar case studies for other locations in the West Nordic region, including Nanortalik in Greenland.

## 1.2 Project Phase I – Feasibility Study

The feasibility study, performed in the period 2004-2005 by ECON (Denmark) and IFE, 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 was performed using constructed load and weather data and a set of generic renewable energy and hydrogen system modeling tools. More information (in Danish and Norwegian) about this work is found in the feasibility study report [1].

## 1.3 Project Phase II – Definition and Evaluation of System Concept

In 2005 it was decided to start up a second phase of the project with more focus on two specific locations: (1) Nólsoy, the Faroe Islands and (2) Nanortalik, South Greenland. The overall objective in Phase II was to gather more detailed information on wind energy and energy demand for the two sites and to develop more pin-pointed 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 2).

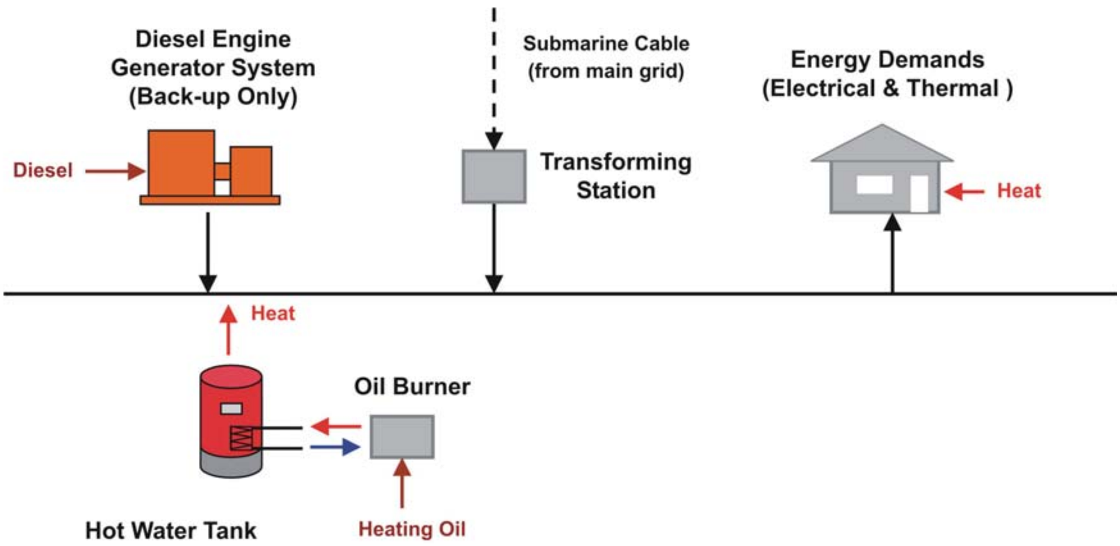


*Figure 2 Schematic of existing (2007) energy system in place at Nólsoy.*

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 1550 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. 1000. The shrimp factory located at the quay was closed down in 2001, but has later been replaced by a crab factory. There is also a seal skin factory in the town. Future development of 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 and hydrogen system concepts for Nólsoy and Nanortalik, more detailed wind energy and load data than what was available in Phase I of the project was required. It turned out that data collection would be easier in Nólsoy than in Nanortalik; partly because of a stronger engagement in the project by local community in Nólsoy and partly because of accessibility to the site (Nólsoy is geographically 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.

### 1.4 Project Phase III – Verification of Specific System Concepts

In 2006 more wind speed data was collected at Nólsoy. In addition, more detailed measurements of the electrical power consumption on the island were made available. This made it possible to perform more detailed technical simulation studies, using more accurate input data (wind and power).

In Phase III of the project most of the effort was spent on verifying the results for the more interesting system configurations proposed in Phase II. A specific focus in Phase III of the project was to perform detailed studies on how excess wind energy in a wind/diesel mini-grid system can be dumped into a large centralized thermal storage and district heating (DIT) system at Nólsoy. The performance of such a DIT-system was compared to a solution based on distributed domestic hot water tanks (DHTs).

Another important task in Phase III of the project was to initiate a wind energy monitoring project in Nanortalik, South Greenland. A survey of buildings in Nanortalik suitable for energy monitoring was also conducted. However, a proper energy survey has still to be performed.

### 1.5 Meetings and Site Visits

Several meetings and site visits were made in order to get a better understanding of the local renewable energy resources and energy mix (electrical and thermal) available at the potential locations for a demonstration system. In May 2005, the project group made a site visit to Nólsoy (Figure 3), as part of the Phase II project kick-off meeting.

In August 2005 two members of the project group (from ECON and IFE) made a site visit to Nanortalik (Figure 4). Information on the general progress in the West Nordic project and specific details regarding the Nólsoy and Nanortalik project development has been reported in internal reports to the Nordic Energy Research.

In September 2005 a site visit was made to Hydro's wind/hydrogen demonstration system at the Utsira Island in Norway (Figure 5). 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 on the technology.

In May 2006 a Masters student from the 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.

In July 2007 Andres Mørkved (previously named Andreas Rinnan) from the IFE-project team visited the Faroe Islands, and presented the latest simulation results at a project meeting with Jarðfeingi (Faroese Earth and Energy Directorate), SEV, Statoil, Hydro (now StatoilHydro), and Enercon. All of the parties at this meeting have shown an interest in developing and realizing a wind/hydrogen demonstration system at Nólsoy.

In September 2007, as part of an effort to disseminate information about the West Nordic project to a larger audience, project results were presented at a Nordic Symposium in Lerwick, Shetland [2].

Quay in Nólsoy

Village of Nólsoy

View to West (towards Tórshavn)

View to South

*Figure 3 Nólsoy, the Faroe Islands (Photos: www.faroeislands.dk)*

View to North (fjord outlets)

View to South

New part of Nanortalik

Old part of Nanortalik

*Figure 4  Nanortalik, South Greenland (Photos: Ø.Ulleberg, 2005)*

Wind turbines (2 × 600 kW)

Hydrogen energy system

*Figure 5  Utsira (Norway) wind/hydrogen energy demonstration system (Photos: Ø. Ulleberg, 2005)*

## 1.6 Scope of Work (Project Phase II and III)

The work described in this report mainly covers the energy system simulation studies and technical analyses performed by IFE during Phase II and III of the West Nordic project. The report, based on an interim report for Phase II of the project [3], includes the final results from detailed simulations based on time series for measured wind data and actual data for the total power consumption at Nólsoy in 2006.

The scope of work for the system analyses performed in Phase II (interim report) of the project was to:

- 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.

The scope of work for the system analyses performed in Phase III of the project was to:

- Collect measured wind data at Nólsoy.
- Collect measured data for electrical power consumption at Nólsoy.
- Perform wind/diesel power system simulations with 10-minute time steps and improved control algorithms, using measured data for wind and power consumption.
- Perform wind/diesel and thermal energy storage system simulations using detailed thermal storage tank models (DIT or DHT) to study the use excess wind energy for space and tap water heating purposes.
- Update the cost of energy (COE) calculations for the most interesting system configurations:
  (1) Wind/diesel (only electrical)
  (2) Wind/diesel with thermal storage (DIT or DHT)
  (3) Wind/diesel with thermal storage and hydrogen production

# 2 Overall System Concept

A schematic of the overall renewable energy hydrogen system concept proposed for Nólsoy in Phase II of the project is shown in Figure 6, while the overall system analyzed in further detail in Phase III is shown in Figure 7.

A comparison of the two figures shows that no further analysis on a heat pump system was proposed in Phase III of the project. This does not mean that heat pumps should be ruled out in the further project development. Actually, from an economical point of view, this should be considered installed before a hydrogen system. Figure 7 indicates that there needs to be a sharp focus in the project on hybrid wind/diesel systems that can provide both power and heat in an energy wise and cost-efficient manner.

Figure 7 also indicates that hydrogen is the most futuristic option, and should mainly be considered to meet local transportation needs, such as fuel for the local passenger ferry and/or small private boats.

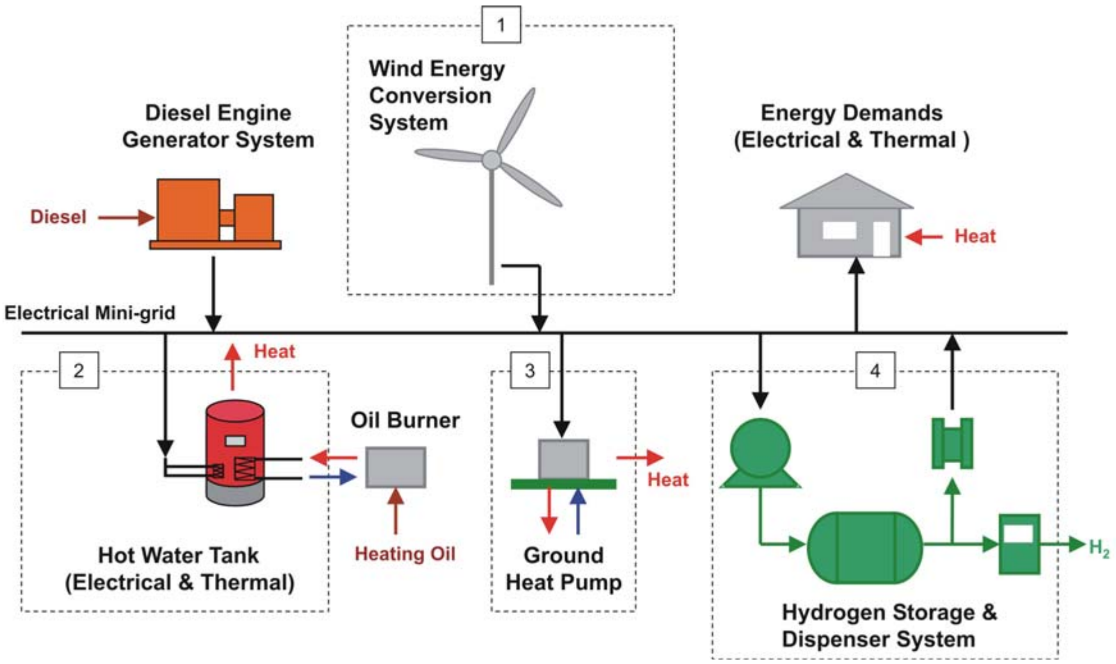


*Figure 6 Overview of proposed renewable energy system concept for Nólsoy in Phase II of the project. Notes: (1) The reference system was a diesel engine for power production and distributed oil burners for heating. (2) Alternative additional sub-systems are labeled 1 to 4; these are proposed added to the reference system in the in the specified order (1 to 4).*

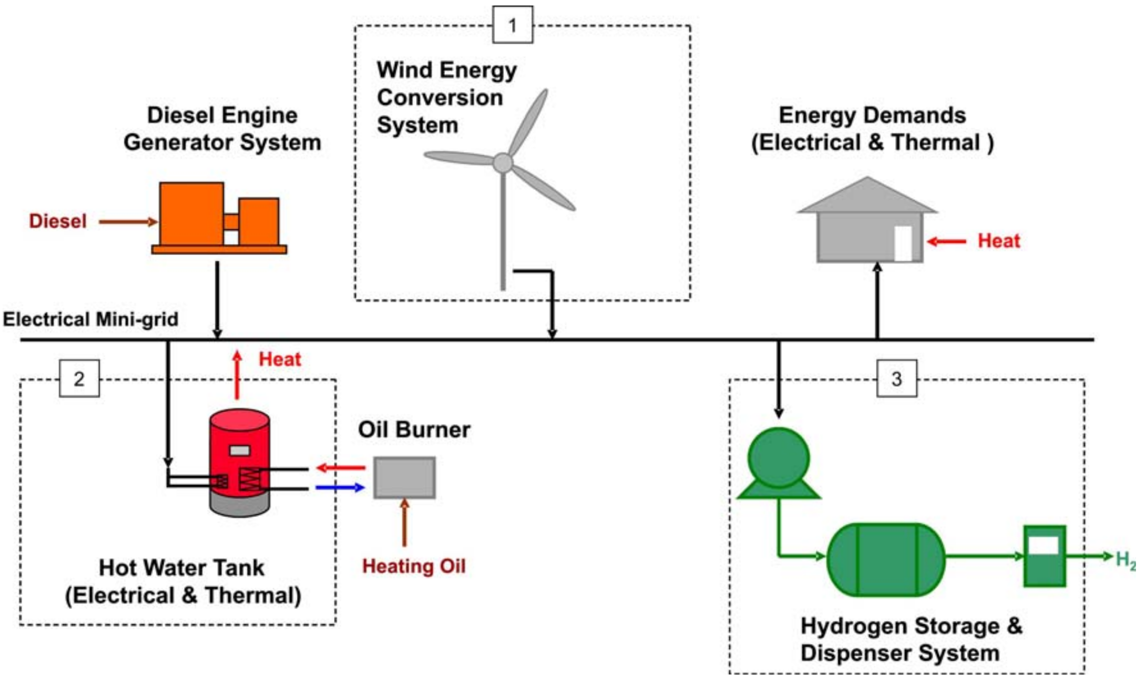


*Figure 7 Overview of proposed renewable energy system concept for Nólsoy in Phase III of the project. Notes: (1) The wind/diesel system design derived in Phase II was used as the reference system in Phase III. (2) Thermal and hydrogen system (sub-systems 2 and 3) were investigated in more detail in Phase III than in Phase II.*

## 2.1 System Description

The basic concept for the power system is to add a wind energy conversion system (WECS) (Figure 6, 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 (Figure 6, 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. 65ºC) and the space heating demands (radiators at ca. 85ºC). A district heating system with a large centralized thermal storage tank (DIT-system) could also be a solution.

A ground heat pump (HP) (Figure 6, System 3) is most suitable if it can be combined with a low-temperature floor-heating system (ca. 35-40ºC). 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 (Figure 6, 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, and electric vehicles) is proposed.

## 2.2 Project Stages

The following six project stages are recommended for the development and implementation of the system concept(s) described in Figure 6 and Figure 7:

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. There exist today fully commercial WECS/DEGS-mini-grid solutions. Hence, the challenge is mainly the financing of the up-front investment. One possible financial model is that the local community establishes a co-operation (co-op) so that the users own the energy system themselves.

4. **DHT or DIT**: Replace existing domestic hot water tanks (DHTs) with new and larger super-insulated multi-source DHTs that allow 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. Alternatively, consider to install a large centralized thermal storage and distribution system, i.e., district heating system (DIT).

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 power system is in place. A one-time grant to reduce 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 project stages above (stages 1-5) have been completed 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 (e.g. in the 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. A research, development, and demonstration project (RD&D) with co-funding from the EU's planned Joint Technology Initiative (JTI) on hydrogen and fuel cells should be considered.

# 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 [4] is shown in Table 2. 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 3).

*Table 2 Annual electricity consumption at Nólsoy 2002-2005[4]*

| **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 2) for Nólsoy was established. For this reason different load profiles for the system analysis were used in the Phase II system simulations performed at IFE and in the Masters study undertaken at NTNU [5]. The Masters study was based on data from 2003 (before closing of the fish farm), while IFE based their calculations on data from 2005. This makes it impossible to compare the simulation results directly. Hence, the conclusions from the Masters study must be interpreted independently from the simulation work performed by IFE.

The electrical mini-grid (400 V) at Nólsoy is today supplied with power from a transforming station connected to a sea cable (10 kV) coming from Tórshavn. Actual measurements of the total electrical power consumption at Nólsoy were not available in Phase II of the project, but were made available in Phase III.

Hence, the Phase II simulations were based on a normalized electrical load profile generated in Phase I of the project [1]. This profile was based on data from Grímsey, Iceland, which is an island community similar to Nólsoy, but slightly smaller. The monthly and daily load profiles used in the Phase II simulations performed at IFE are shown in Figure 8 and Figure 9, respectively.

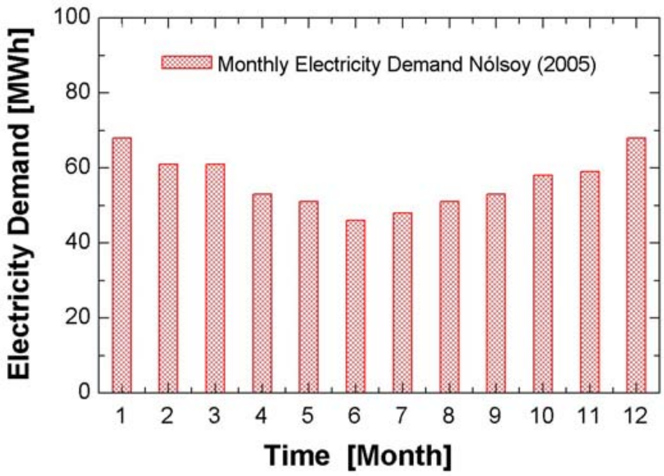


*Figure 8 Monthly electricity demand assumed for the entire mini-grid at Nólsoy (Phase II study)*

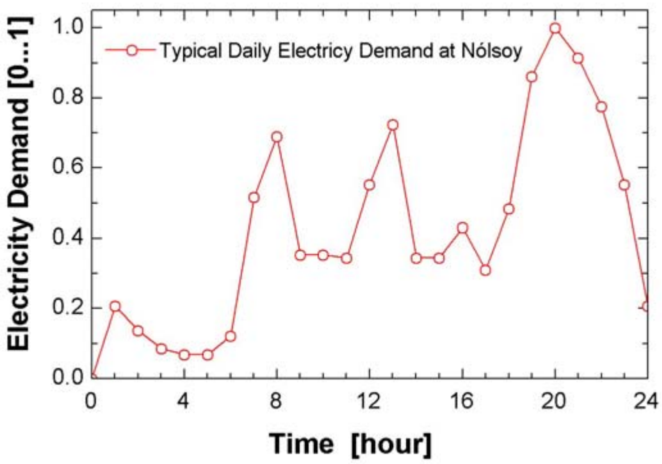


*Figure 9 Daily electricity demand profile assumed for Nólsoy (Phase II study).*

The simulations performed in Phase III the project were based on actual power measurements made at the transforming station at Nólsoy, which is connected to the sea cable (10 kV) from Tórshavn. Electrical power data with 15-minute resolution for the period 15 July – 31 December 2007 was obtained from SEV, the national power company on the Faroe Islands. The main objective with SEV's power monitoring program was to quality assure power production on the island, i.e., to ensure that the voltage is within proper limits. Hence, only data with 15-minute resolution was available.

The half-year (170 days) time series with measured power data used as the basis for the Phase III simulations was more or less intact, except for a few "holes" in the data set. In total about 2.5 days of data was missing from the 170 days time series. The holes in the data series were fixed using statistical methods. Figure 10 shows the 15-minute 170-day time series used as basis for the simulations in Phase III of the project.

In order to make the simulation input power demand profile consistent with the measure input wind speed data (Figure 12), the resolution on the measured power time series (Figure 10) was converted from 15-minute resolution to 10-minute resolution using linear interpolation techniques.

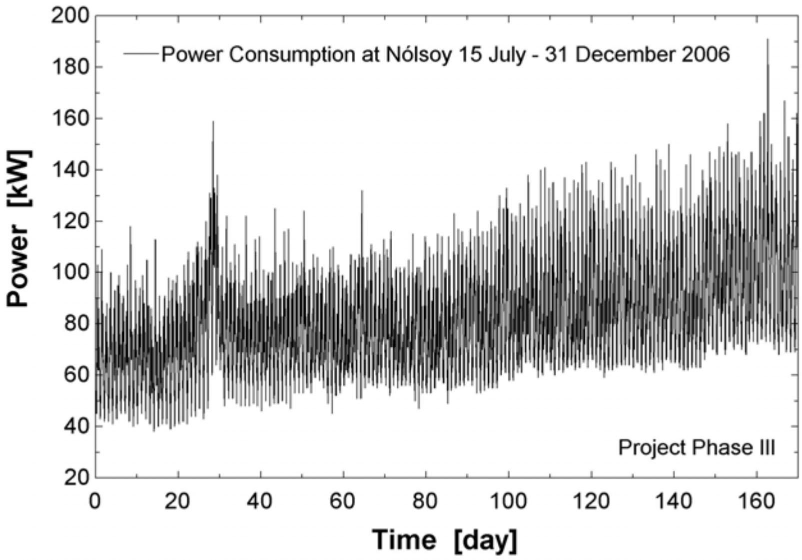


*Figure 10 Power consumption measured at the transforming station in Nólsoy used as basis for the system simulations in Phase III of the project.*

## 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 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 Phase II of the 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 gave useful insight to the data made available by the two oil companies. A detailed description of the survey and subsequent data analysis is available in a separate study [5], 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 [6]. 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 $kWh_{th}$ [7]. 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. Because of 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 [8]. 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) [5]. This is equal to about 15% of the total heating demand, which compares well with the Norwegian average of 15-20% [9].

As shown above (Phase II study) the total thermal energy demand (space heating and tap water) for an average household at Nólsoy was estimated to be 27000 $kWh_{th}$. For the Phase III simulations simple normalized heat demand profiles for week-days and week-ends were developed. The week-day profile was estimated based on typical operation of the existing oil burners installed in the houses at Nólsoy. During the week these typically operate from early afternoon until midnight, indicating that most people at Nólsoy do not use their oil heaters during the morning (on week-days). On the week-ends it was assumed that people use the oil heaters from mid-day until midnight, resulting in an increased daily heat demand compared to the weekdays.

The monthly variation in the heat demand was assumed to depend more on the wind speed than on the outside temperature. Long-term climate statistics from Torshavn (1961-2000) show that Nólsoy has a mild coastal climate, with a low average temperature difference between the coldest and warmest month in the year (only about 6 °C). Thus, it is likely that the wind speed conditions at Nólsoy will have a greater effect on the space heating demand than the temperature conditions. Hence, in the annual heat demand profile used in the Phase III simulations it was assumed that the month with greatest wind speed also was the month with the highest thermal energy demand.

### 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 be able to join 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 at Nólsoy, Bjarti Thomsen and Dávur Juul Magnussen, who revised and adjusted the questionnaire for local conditions, and translated it to Faroese. 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 3, 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 $kWh/m^2$ [7]. 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 3 Summary of energy survey at Nólsoy performed in April/May 2006 (Phase II study)*

| 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 3), and a good overview of the overall energy infrastructure on the island. However, the relatively low rate of response also indicates that the survey could have been made more user-friendly (e.g. more visually appealing). The survey 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

Synthesized hourly electricity power demand profiles (Figure 8 and Figure 9) were used in the Phase II wind/diesel power system simulations, while a measured power demand curve for Nólsoy (Figure 10) was used for the Phase III system simulations. The space heating demand profiles used in the wind/diesel with thermal storage system simulations in Phase II and III were both derived from the estimated overall thermal energy demand (27000 $kWh_{th}$/year in total, hereof 4000 $kWh_{th}$/year for hot tap water). A daily heat demand profile for a typical household at Nólsoy was synthesized for the Phase III system simulation. A simple step-function (constant base and peak load) for the thermal heat load was synthesized (Figure 33). The daily average heat demand (low in the summer and high in the winter) were calculated from the overall thermal energy balance and the wind chill factor.

# 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, are 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 [10].

In order to get an exact estimate for the wind energy potential at Nólsoy it was decided to install a 30 meter mast with 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 11). 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 31 meters) with 10-minute intervals. The wind data is automatically transmitted and uploaded to a web site at Risø National Laboratory in Denmark.

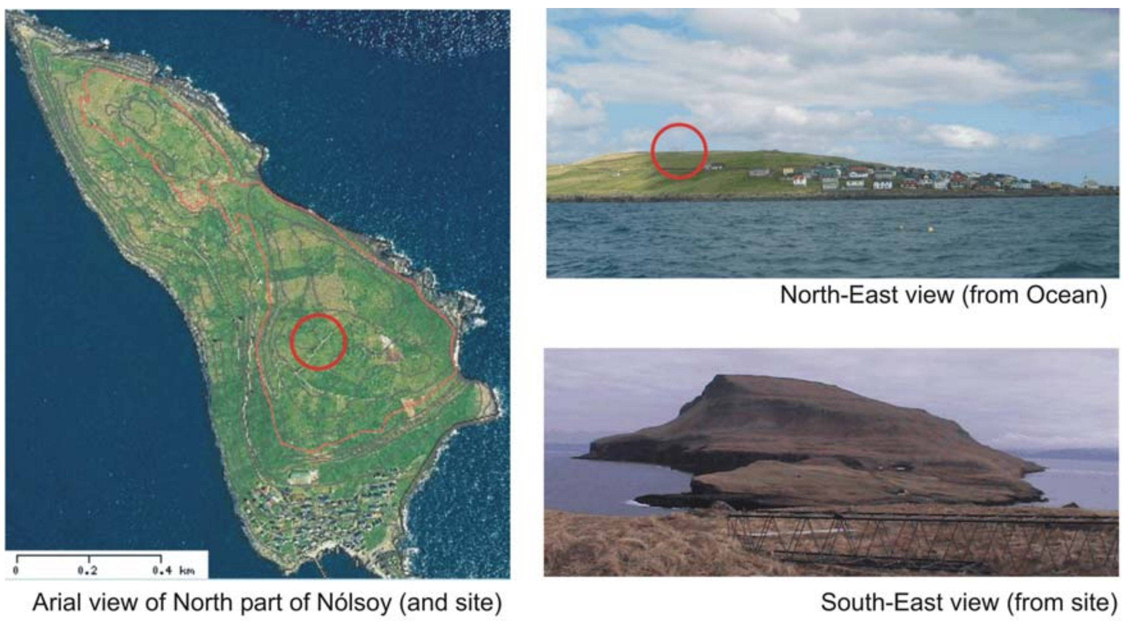


*Figure 11 Overview of the site chosen for wind energy measurements at Nólsoy.*

A plot of the wind speeds measured from 10 March 2006 to 17 February 2007 is shown in Figure 12. The regularity of the wind speed measurements was satisfactory, except for a few holes in the recordings here and there. Over the first year (or ca. 350 days) more than 48200 wind speed records were made, which is about 97% of a complete time series. These 10-minute wind speed measurements were used as a basis for the Phase II and III system simulations, as described below.

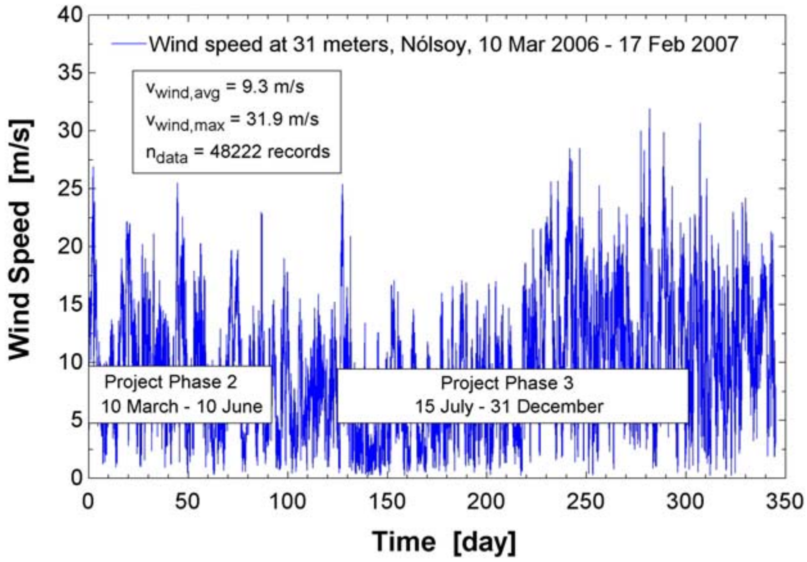


*Figure 12 Wind speed measurements at Nólsoy for the period 10 March 2006 – 17 February 2007. Data collected every 10 minutes at 31 meters, with time series used as basis for the Phase II and Phase III system simulations indicated.*

Only three months (10 March – 10 June) with measured wind speed at Nólsoy was available for the system simulations performed in Phase II of the project. This 3-month time series (Figure 12, left) was used to synthesize an hourly annual wind speed profile. This was done by using a simple linear correlation between the wind speed at Nólsoy and a reference station at Mykines Fyr. The annual wind speed profile for the reference station (based on long-term data) was calculated in Phase I of the project [1]. Based on this an annual hourly wind speed profile could be synthesized for the Phase II system simulations.

The system simulations performed during Phase III of the project was based on 10-minute wind data for the 6-month period 15 July – 31 December (Figure 12, right). This time period corresponded with the time period for the power measurements made at Nólsoy (Figure 10). A closer look at the wind data from 2006 shows that there is a gradual build-up of the wind from summer (July) to winter (December). This is the same trend as found in the long-term data from Mykines Fyr [1]. The same long-term data shows that the trend is opposite in the spring, i.e., the wind decreases going from winter to summer. Hence, in the Phase III simulations and energy calculations, the wind energy profile for the first half of the year (January to June) was assumed to be exactly opposite to the wind profile for the second half of the year (July to December) (Figure 12, right).

# 5 System Analyses and Simulations (Phase II Study)

This chapter and the next summarize the main results from the Nólsoy system analyses and simulation studies undertaken in Phase II and III of the West Nordic project. The purpose with this chapter is to describe, define, and evaluate the various system configurations described in Figure 6. The focus in the next chapter is to perform more detailed simulations of the system(s) described in Figure 7, using more accurate simulation input data. In order to avoid confusion, descriptive text, figures, graphs and tables are all marked explicitly with "Phase II study" or "Phase III study".

## 5.1 Simulation Modeling Tools (Phase I, II, and III)

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 and III of the project the focus was 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. In Phase III of the project an improved wind/diesel-controller developed by Todd Houstein, a PhD-student at the University of Tasmania [reference], was also integrated into 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, 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 from 56 different organizations in 20 countries were registered. About 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 [11,12]: (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 on the domestic hot water tank (DHT), is found in a related Masters study [5].

A summary of the economic parameters and cost functions used in a post-simulation "Economizer Model" coupled to the TRNSYS output files is provided in the Appendix.

## 5.2 Reference Diesel System (Phase II)

A stand-alone diesel engine generator system was selected as the reference system (Figure 13) for the base case simulation studies performed in Phase II.


*Figure 13 Reference system (Phase II study).*

An annual simulation of the reference system (Figure 13) based on the electricity demand profile for Nólsoy (Figure 8 and Figure 9) 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$_{el}$.

The annual emissions from running the system entirely on diesel fuel is significant, but just as important is the environmental costs and risks of transporting and storing the fuel locally (Figure 14) (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).

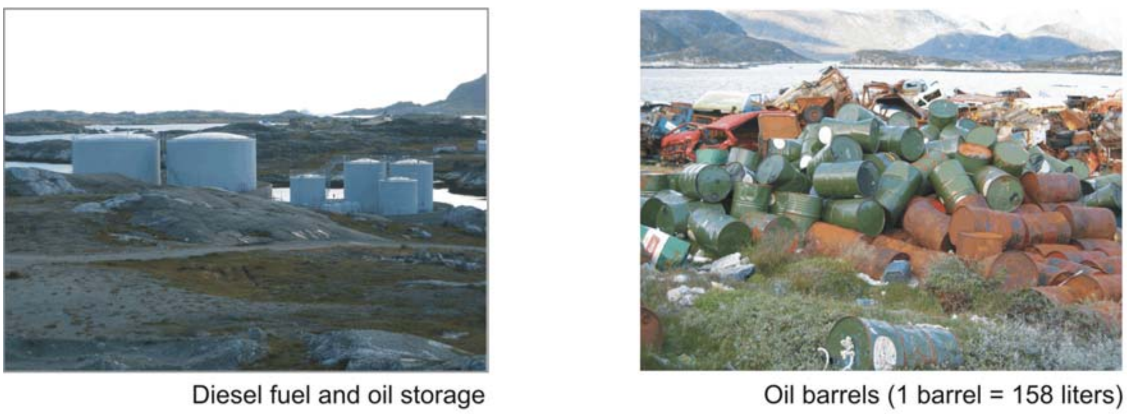


*Figure 14 Diesel fuel and oil storage in Nanortalik, South Greenland (Photos: Ø. Ulleberg, 2005).*

## 5.3 Wind/Diesel System (Phase II)

The first alternative system considered in the Phase II 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 15). The main objective with this system concept is to displace as much diesel fuel as possible by using local wind energy available at Nólsoy.

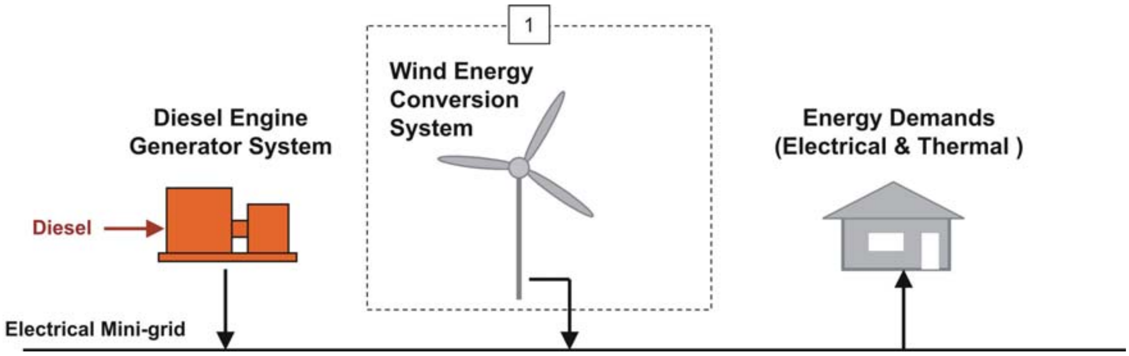


*Figure 15 Wind/diesel power system (Phase II study).*

Annual simulations of a wind/diesel system (Figure 15) based on the electricity demand profile for Nólsoy (Figure 8 and Figure 9) and a synthesized annual wind energy profile, based on 3-months wind data from Nólsoy (Figure 12), was performed for various system configurations. Table 4 summarizes the main results for the diesel only and wind/diesel system simulations performed.

The results (Table 4) 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 4 Comparison of key design parameters and corresponding main results for the Nólsoy diesel only (reference) and wind/diesel system simulations (Phase II study).*

| | **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 Hot Water Tanks (Phase II)

The second basic alternative system considered in the Phase II study was a wind/diesel system with distributed domestic hot water tanks (DHTs) for hot tap water and/or space heating (Figure 16). At Nólsoy almost all of the households have installed oil-fired hot water radiators (Table 3). 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).

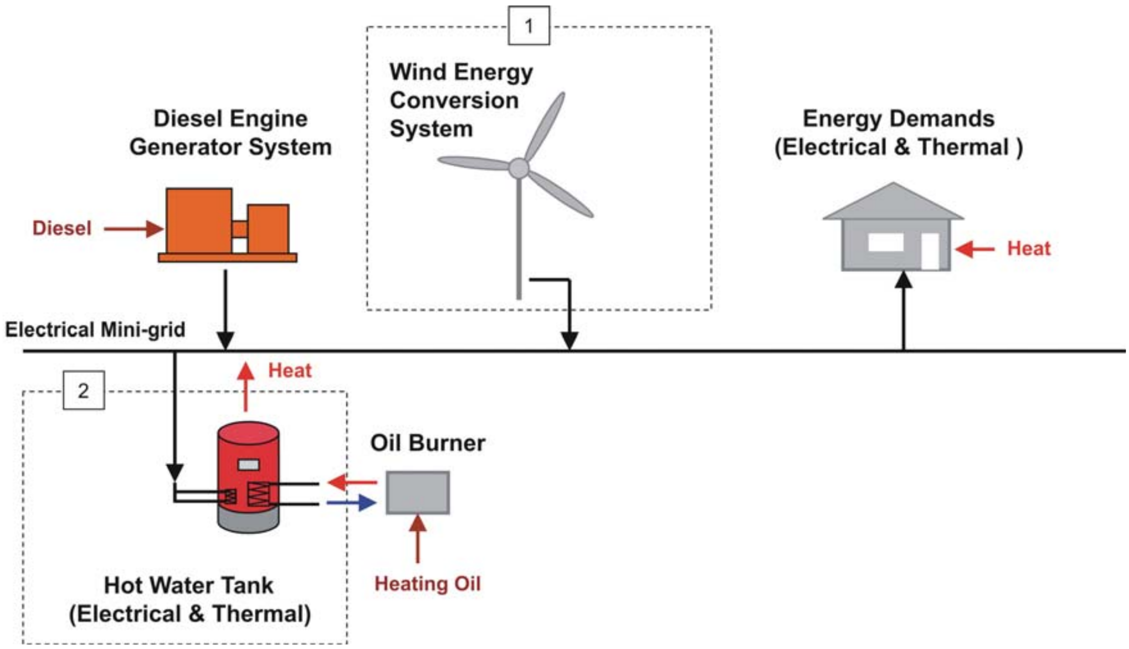


*Figure 16 Wind/diesel energy system with distributed domestic hot water tanks (Phase II study).*

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 16). 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 a 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 were made for the system configuration described in Figure 16. The first assumption was 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 was 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 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 17, is typically equipped with a 3-6 $kW_{el}$ (60-90°C thermostat) electrical heating element and a 26 $kW_{th}$ (at $\Delta T$ = 20 °C) thermal heat exchanger. These tanks typically come in sizes of 150, 200, and 300 liters, and cost ca. 800-1000 € per tank, depending on the size.

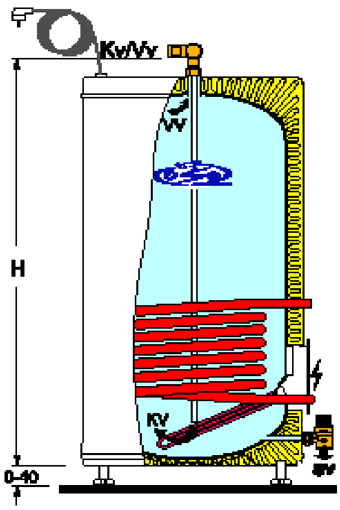


*Figure 17 Multi-source domestic hot water tank (Source: www.oso.no)*

In practice, the individual DHTs in a wind/diesel/DHT-system (Figure 16) 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 $\Delta T$ = 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 Additional DHT System Simulations (Phase II/MSc-study)

Additional simulation studies of various wind/diesel/DHT-system configurations (Figure 16) were performed in a Masters study [5] related to the West Nordic project. Only the main technical conclusions from this MSc-study are included in this report. (More detailed cost calculations were carried out in system simulations performed in project Phase III.)

The main inputs, key design parameters, and main results from the separate wind/diesel/DHT-system simulations performed in [5] are summarized in Table 5. It should be noted that the assumed electricity demand (Table 5) was twice that assumed in the other simulations performed in the Phase II study (Table 4). Hence, the results from the MSc-study must be treated independently from the studies performed in this project.

In the simulation of the wind/diesel/DHT-systems tap water configuration (Table 5, 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 used 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 5 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 €/$kWh_{th}$).

[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 genset, 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 5 Summary of main inputs, key design parameters, and corresponding main results for the Nólsoy wind/diesel/DHT system simulations [5] (Phase II/MSc-study)*

| | **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 (Phase II)

The main conclusion from the technology evaluations and detailed thermal energy system simulations described and discussed 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 16).

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 large tanks (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. More detailed cost calculations were performed in the Phase III simulations, which were based on more long-term wind speed data and more realistic thermal and electrical energy demand profiles.

## 5.5 Heat Pump System (Phase II)

The feasibility of attaching a heat pump system to a wind/diesel mini-grid (Figure 18) so that it can meet the space heating demand for a larger building in Nólsoy was investigated in a separate Phase II case study.

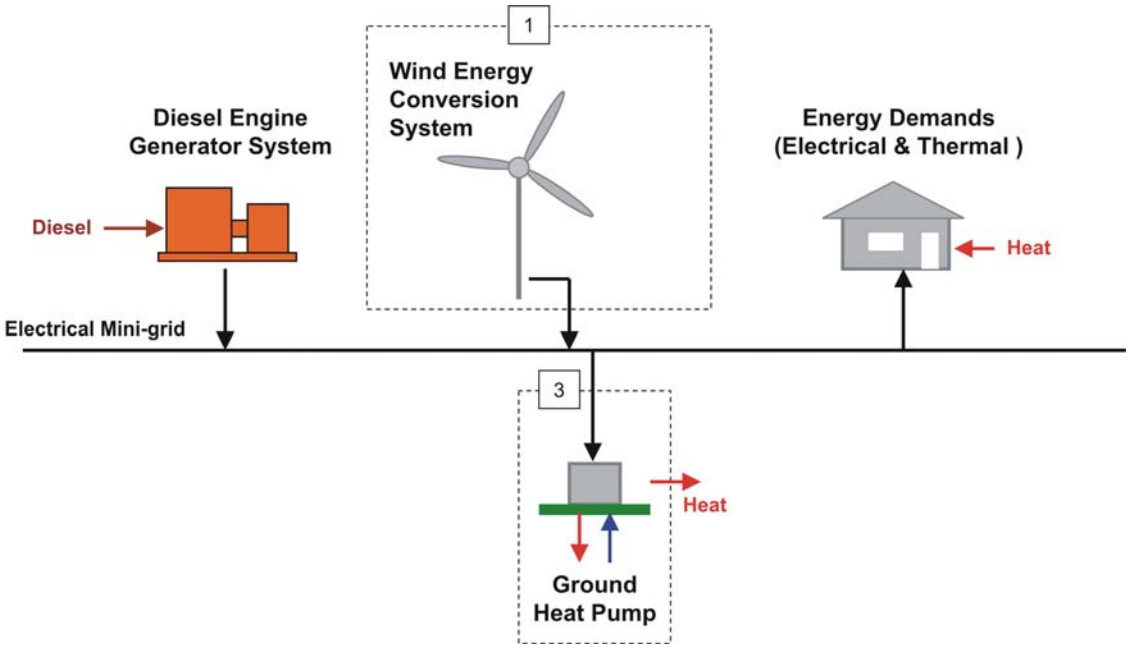


*Figure 18 Wind/diesel/heat pump system (Phase II Case study 1).*

### 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 such 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 19, which shows the typical relationship between *COP* and temperature rise, i.e., the difference between the inlet (heat sink) and the outlet temperature.

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 20.

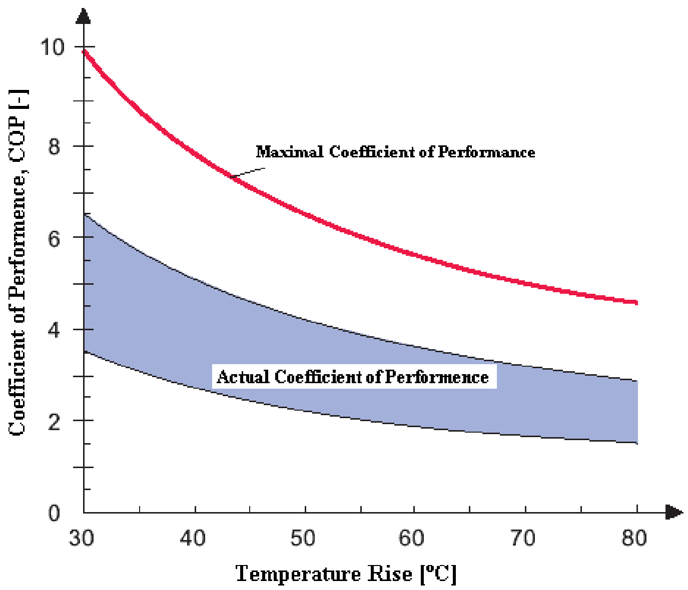


*Figure 19  Heat pump characteristics; coefficient of performance (COP) vs. temperature rise (ΔT) [13].*

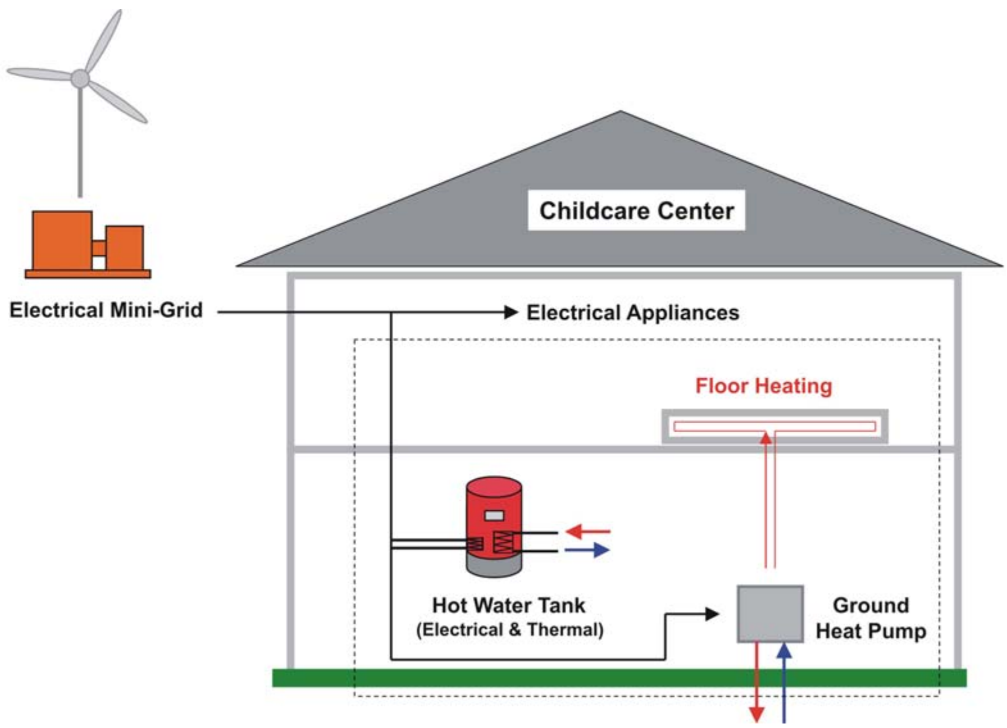


*Figure 20  Heat pump system (system boundary indicated by dotted lines) proposed for childcare center at Nólsoy (Phase II study).*

### 5.5.2 Results from Heat Pump System Simulations (Phase II)

The design of the heat pump/floor heating system shown in Figure 20 (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 6.

*Table 6 Summary of main inputs, key design parameters, and corresponding main results for the Nólsoy heat pump system simulations (Phase II study)*

| Item | Specification | Comments & Assumptions |
|---|---|---|
| **Main Inputs:** | | |
| Specific thermal energy demand | 40 W/m² [13] | *U*-values for new homes assumed [14] |
| 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 6) 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 20), should easily be handled by a stand-alone hybrid wind/diesel mini-grid power system (Figure 18).

### 5.5.3 Heat Pump System Conclusions and Recommendations (Phase II)

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 (typical demand for a household at Nólsoy) is provided in Table 7. 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 4), 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 5) 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 7 Economic comparison between typical water-to-water and air-to-air heat pumps (Phase II study).*

| | 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 (Phase II)

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 21) on Nólsoy is discussed below, in a separate Phase II case study. More detailed simulation studies of this concept, based on more complete wind speed and electricity demand profiles, were performed in Phase III of the project.

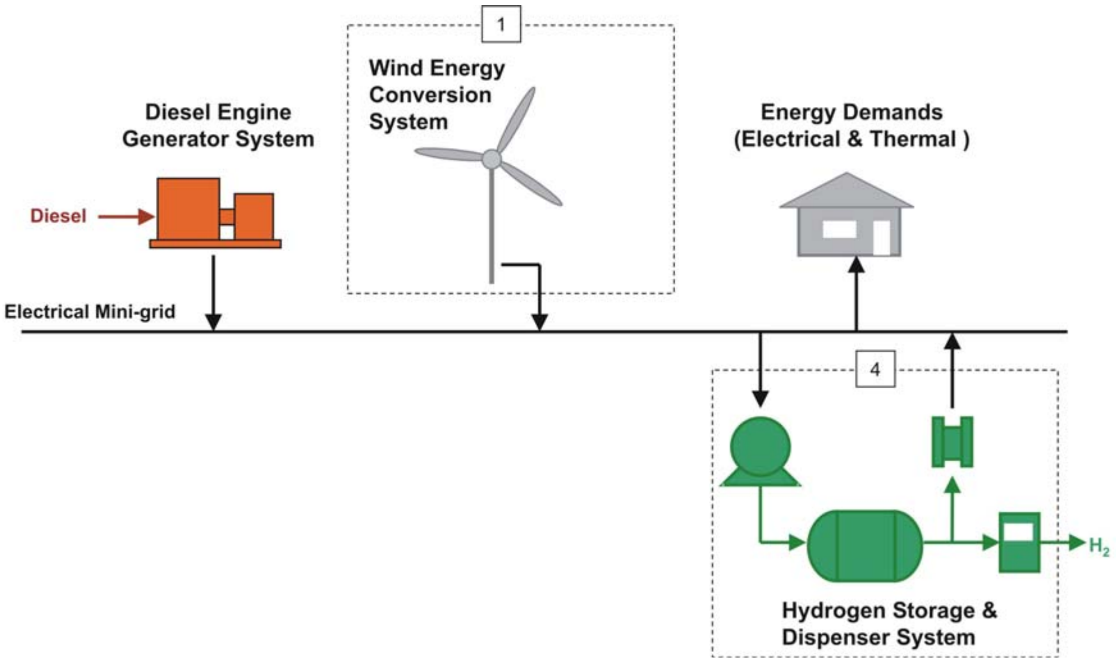


*Figure 21 Wind/diesel/hydrogen system (Phase II study).*

### 5.6.1 Basic Hydrogen Storage and Dispenser System Concept (Phase II)

The basic idea behind the hydrogen storage and dispenser system shown in Figure 21 is to maximize the use of the installed electrolyzer hydrogen production capacity, while 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 [12]. 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%), an 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 will be even greater.

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 needs 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 [15]) 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 System (Phase II)

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 21).

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 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:

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

This 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/Nm3. 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 15 and Table 4). 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 for 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 22, which indicates 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 Utsira (Figure 5) had a capacity of about 2400 $Nm^3$.

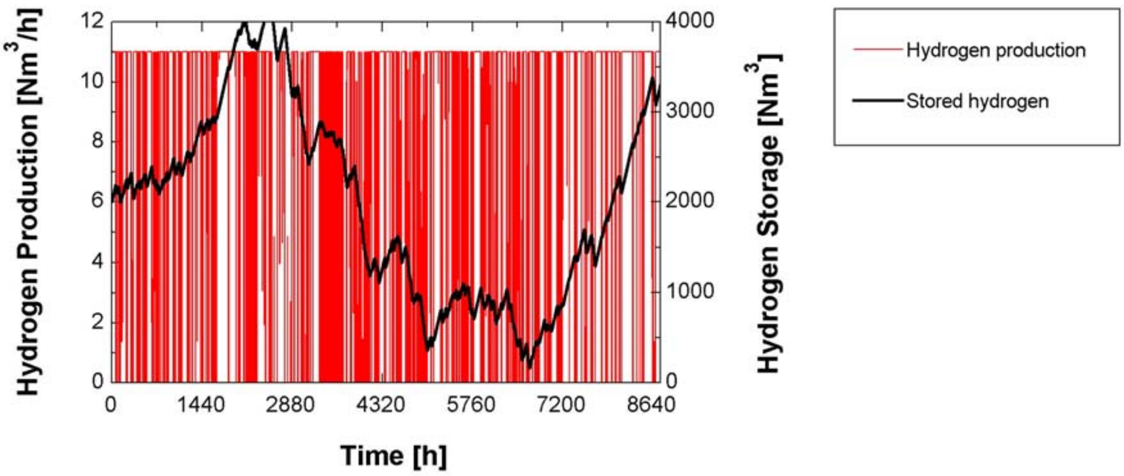


*Figure 22 Hydrogen production and storage in a possible hydrogen system located in a wind/diesel mini-grid at Nólsoy.*

The results above indicate that it is both theoretically and practically possible to build a hydrogen storage system at Nólsoy that all-year round can deliver hydrogen based 100% on renewable energy. The next step would be to investigate alternative designs for a hydrogen fuel cell driven 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 Detailed System Simulations (Phase III Study)

The main objective with the detailed system simulations performed in Phase III of the West Nordic project was first of all to verify the techno-economic viability of introducing a wind/diesel and district heating system to the island of Nólsoy, as illustrated in Figure 23.

The second objective was to evaluate the effect of adding extra wind power capacity to a wind/diesel/DIT-system, and to see if the excess wind energy could be used to produce hydrogen for a local ferry, as illustrated in Figure 7.

All of the Phase III simulations were based on measured power consumption (Figure 10) and wind speed data (Figure 12) at Nólsoy for the half-year period 15 July – 31 December 2006. Hence, the results from the Phase III simulation studies should be more accurate and realistic than the results obtained in earlier phases of the project.

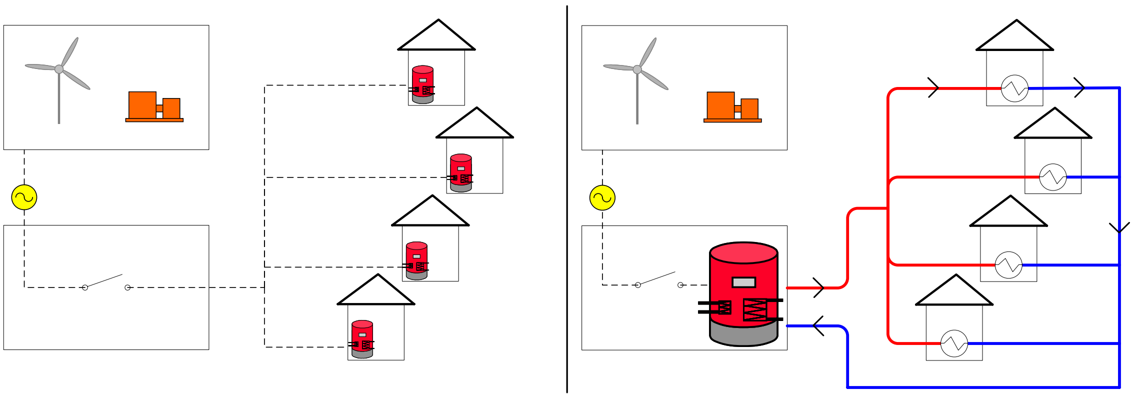

*Figure 23 Wind/diesel mini-grid system with two alternative water heating system configurations.*
*Left: DHT – Distributed domestic hot water tanks (Phase II study)*
*Right: DIT – District heating system (Phase III study)*

The main difference between a system based on distributed domestic hot water tanks (DHTs) (Phase II study) versus a system based on a centralized district hot water tank (DIT) (Phase III study), is that DITs require insulated heat pipes for heat distribution, while DHTs require sufficient capacity on the local electrical grid (Figure 23). The heat losses from the hot water storage tank itself decreases with increasing size (reduced surface area per volume).

The relatively large heat loss per volume in small distributed DHTs could potentially be a disadvantage. However, this may not be such a big issue, as the DHTs in most cases can be placed inside the space heating zones of the houses or the buildings to be heated. In the case of a district heating system (DIT) there will be heat losses from the distribution pipes. These heat losses from the distribution pipes are not accounted for in the calculations performed in study, as this requires detailed knowledge of the distribution heating system.

A "screening" of possible wind/diesel/DHT-system configurations was in effect done through the case studies performed in Phase II of the project. Table 8 shows the three specific system design parameters that were investigated in the more detail in the Phase III system simulations.

*Table 8 System design parameters and component capacities investigated in the Phase III simulations.*

| **System Design Parameters** | **System Component Capacities** (1) | | | |
|---|---|---|---|---|
| $P_{WECS}$ – Rated power for the wind energy conversion system [kW] | 100 | 225 | 300 | 605 |
| $P_{DEGS}$ – Number of and rated power for the diesel engine generator system [kW] | 3 × 80 = 240 | | 2 × 120 = 240 | |
| $V_{DIT}$ – Volume of the thermal storage [liters/house] | 1000 | | 2000 | |

(1) Sixteen (4 × 2 × 2 = 16) possible system configurations in all.

Four basic system evaluation parameters were selected in order to compare the results from the different system simulations:

1. Cost of energy (*COE*) for electric and thermal energy, €/kWh
2. Fossil fuel (diesel and heating oil) consumption, liters/year
3. System installation cost, M€
4. Renewable energy utilization, %

These parameters were selected so that a well-balanced evaluation could be made. As demonstrated earlier in the West Nordic project (Phase I and II) these parameters reflect both the economic and environmental aspects that the local authorities, energy company, project developers, and local community (energy consumers) all need to consider before deciding to invest in a long-term (20-30 years) renewable energy project.

## 6.1 Reference Wind/Diesel System (Phase III)

The Phase II study indicated that the introduction of a wind turbine into an existing diesel mini-grid system could be justified, both from a technical and economical point of view. Hence, in the Phase III study a stand-alone wind/diesel system with a simple oil heater for space and tap water heating (exists for most household at Nólsoy) was used as the reference system, as shown in Figure 24. The specific capacities for the selected reference system were:

- Rated DEGS power: 240 kW
- Rated WECS power: 100 kW
- Electricity demand: 722 MWh/year
- Heating demand: 2711 MWh/year

An annual simulation of the reference system based on actual power consumption (Figure 10), measured wind speed data (Figure 12), and a synthesized thermal load profile, as described in further detail below (Chapter 6.3.2).

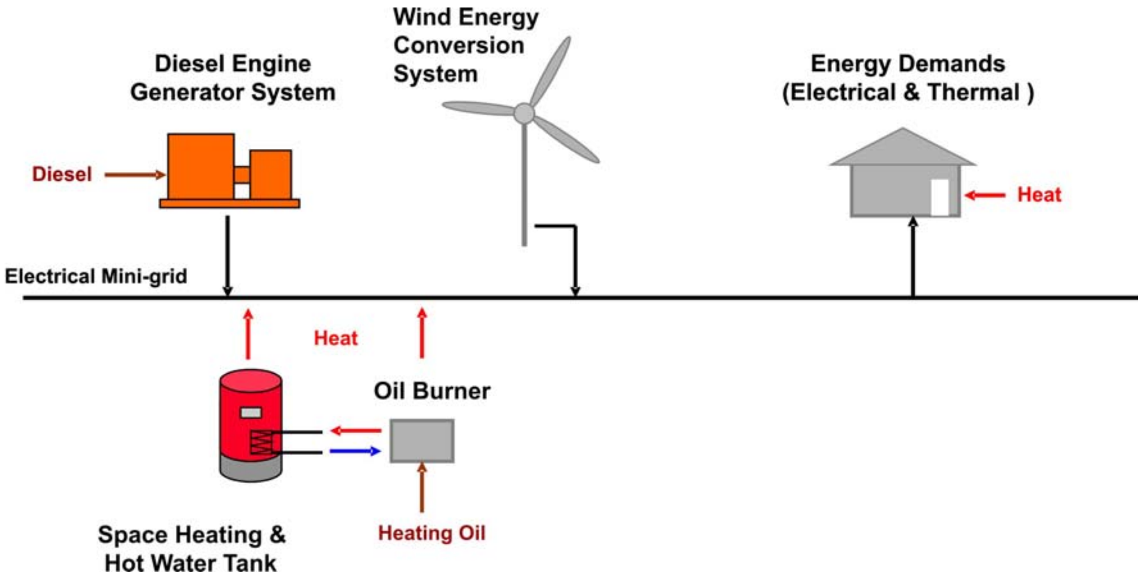


*Figure 24 Reference wind/diesel mini-grid system for the Phase III study.*

The results from the annual simulations are summarized in Table 9. The results show that the reference system has a relatively high renewable energy penetration (50%), given the fact that it is a wind/diesel system with conventional operation of the diesel engine gensets. Wind energy utilization in similar systems around the world is often not higher than 20-30%. The simulations are likely to over predict the power production somewhat, due to inefficiencies not accounted for. Nevertheless, the results indicate that Nólsoy is a very favorable site for hybrid wind/diesel systems. This is also indicated by the calculated cost of energy ($COE$ = 0.19 €/kWh$_{el}$), which is quite reasonable. The reference system will have the lowest investment cost of the systems analyzed in the Phase III study.

*Table 9 Main results from annual simulation of the reference system (Phase III study). System design: $P_{WECS}$ = 100 kW; $P_{DEGS}$ = 2 × 120 = 240 kW).*

| System Evaluation Parameter | Specification | Value | Unit |
|---|---|---|---|
| Cost of energy (COE) | Electricity | 0.19 | €/kWh$_{el}$ |
| | Heat | 0.09 | €/kWh$_{th}$ |
| Fossil fuel consumption | Diesel | 142 700 | liters/year |
| | Heating oil | 332 900 | liters/year |
| Investment cost [(1)] | Overall System | 0.190 | M€ |
| Renewable energy utilization [(2)] | Electricity | 50 | % |
| | Heat | 0 | % |

[(1)] Only main system components. Engineering and civil works is not included.
[(2)] Fraction of wind energy that meets an electrical and/or thermal energy demand.

## 6.2 Sensitivity Analysis wrt. Rated Wind Turbine Power (Phase III)

A sensitivity analysis with respect to the rated wind turbine power, a key system design parameter, was performed based on the reference system described above (Phase III study). The effect of varying the rated wind turbine powers ($P_{WECS}$ = 100, 225, 300, or 605 kW) was analyzed in detail. The results, summarized in Figure 25 and Table 10, show that a DEGS with a minimum capacity of about 160 kW would be required to cover the deficit power, independently of the size of the WECS. The most frequent operating set-point for the DEGS would be 60 kW. This information is also useful for the further design of alternative wind/diesel system configurations that aim at utilizing and/or storing the excess power available, either in a DIT or a hydrogen system.

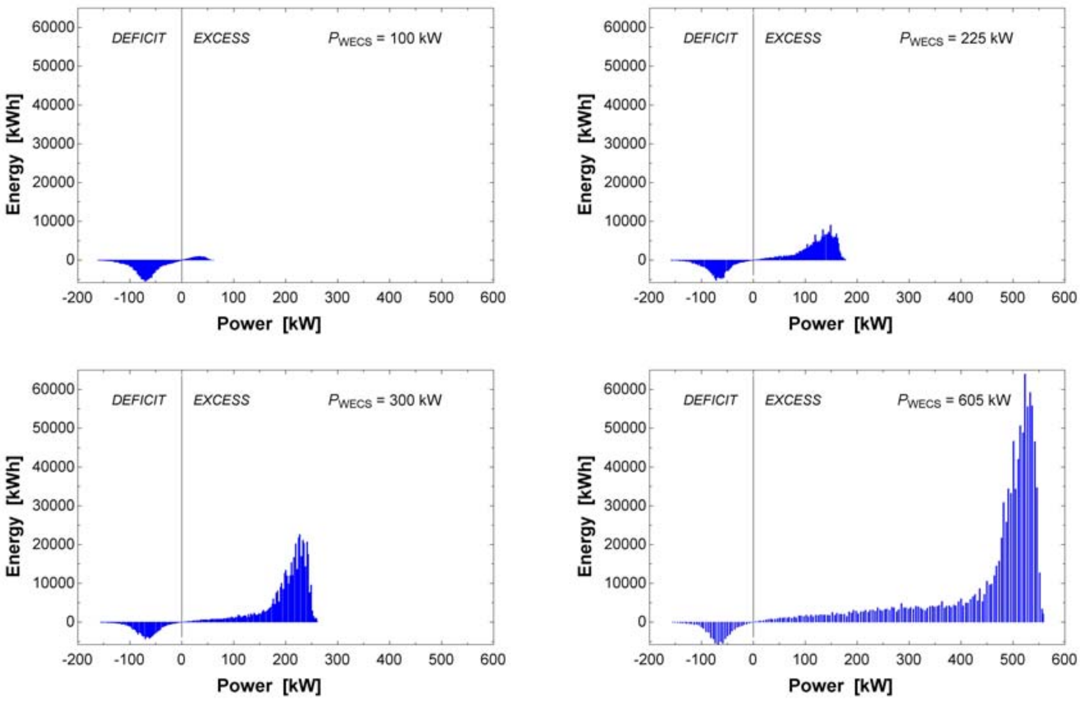


*Figure 25 Sensitivity analysis wrt. rated wind turbine power (Phase III study): Frequency plots for electrical energy versus power for four different wind power ratings ($P_{WECS}$ = 100, 225, 300, or 605 kW). x-axis: Power = Wind Power – Power Demand. y-axis: Energy = Wind Energy – Energy Demand. (Deficit must be covered by back-up system, e.g. diesel gensets).*

*Table 10 Statistics for sensitivity analysis shown in Figure 25 (Phase III study).*

| **Available Power** | **Rated Wind Turbine Power** | | | |
|---|---|---|---|---|
| | **100 kW** | **225 kW** | **300 kW** | **605 kW** |
| Average (median) excess power, kW | 21 (21) | 100 (111) | 172 (198) | 360 (456) |
| Average (median) deficit power, kW | -53 (-56) | -59 (-61) | -57 (-58) | -55 (-57) |

### 6.3 Wind/Diesel System with District Heating (Phase III)

The next system configuration investigated in Phase III of the project was a hybrid wind/diesel system with district heating (DIT). The objective here was to investigate in detail the possibility to store excess energy in the form of heat in a large centralized multi-fuel hot water storage tank. The idea with this concept would be to capture all of the excess wind power after the electrical load has been met. (Dumped power from the diesel engine generator system during idling could also be captured).

The excess electrical energy from the WECS and DEGS was assumed converted into thermal energy through a resistive heater in the hot water tank (DIT), while the oil heater was only used to boost the temperature if needed. Capture of waste heat from the diesel engine generator system was not included in the simulations performed here, and was left for future studies. A schematic of the hybrid WECS/DEGS/DIT-system simulated in Phase III is shown in Figure 26.

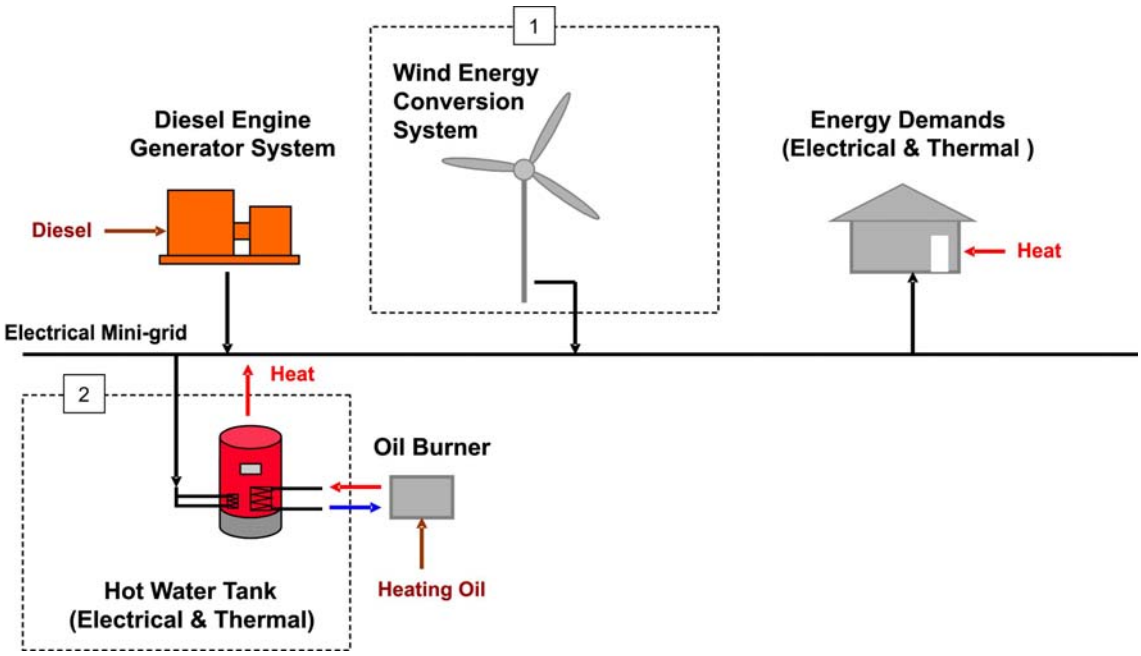


*Figure 26 Wind/diesel energy systems with a large hot water tank (district heating) (Phase III study).*

Two comments on the WECS/DEGS/DIT-system described above should be made:

1. In general, using high-grade electricity for low-grade heating purposes is not good practice. However, for a stand-alone power system located at Nólsoy (or at a similar site in the West Nordic region) the alternative is simply to dump the excess power. There are here not many alternative renewable energy based heating options either.
2. The process of converting fossil fuel to electricity (in DEGS), and later converting this to heat in resistive heaters is not energy efficient. However, in a hybrid wind/diesel system there exist operating conditions (idling of DEGS) where this can be justified.

All possible system design configurations (Table 8) of the hybrid WECS/DEGS/DIT-system (Figure 26) were simulated. Previous simulations (Phase II study) showed that it was more optimal to design a system with 3 × 80 kW diesel generators compared to a system with 2 × 120 kW. This is in agreement with the sensitivity analysis above (Figure 25), which showed that the average power deficit in the system was about 60 kW (Table 10). The results for the most favorable system configuration ($P_{WECS}$ = 300 kW; $P_{DEGS}$ = 3 × 80 = 240 kW; $V_{DIT}$ = 1000 liters/house) are presented in Table 11 and Figure 27.

*Table 11 Main results from annual simulation of the WECS/DEGS/DIT-system (Phase III study). System design: $P_{WECS}$ = 300 kW; $P_{DEGS}$ =3 × 80 = 240 kW; $V_{DIT}$ = 1000 liters/house.*

| System Evaluation Parameter | Specification | Value | Unit |
|---|---|---|---|
| Cost of energy (COE) | Electricity | 0.07 | €/$kWh_{el}$ |
| | Heat | 0.06 | €/$kWh_{th}$ |
| Fossil fuel consumption | Diesel | 120 360 | liters/year |
| | Heating oil | 194 740 | liters/year |
| Investment cost (1) | Overall System | 0.810 | M€ |
| Renewable energy utilization (2) | Electricity | 75 | % |
| | Heat | 35 | % |

(1) Only main system components. Engineering and civil works is not included.
(2) Fraction of wind energy that meets an electrical and/or thermal energy demand.

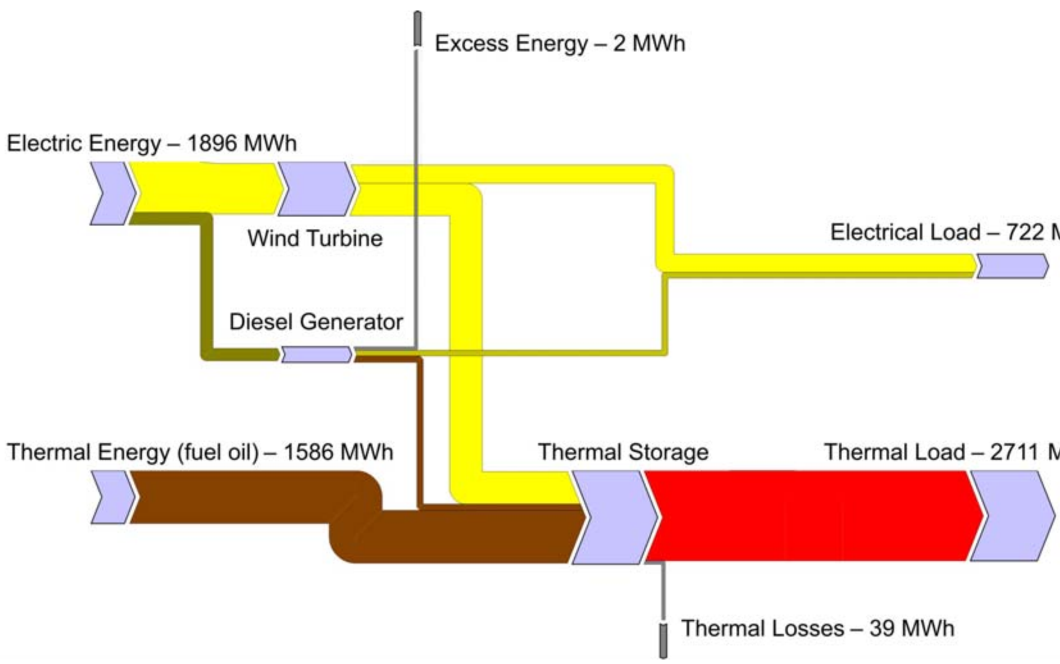


*Figure 27 Energy flow diagram for annual simulation of WECS/DEGS/DIT-system (Phase II study). System design: $P_{WECS}$ = 300 kW; $P_{DEGS}$ =3 × 80 = 240 kW; $V_{DIT}$ = 1000 liters/house.*

The results in Table 11 and Figure 27 show that it is advantageous to add hot water storage into a wind/diesel-system, as this has the potential to capture 100% of the wind energy available. Actually, the thermal system is able to capture more wind energy than the electrical system, illustrated clearly in the energy flow diagram in Figure 27. The proposed system has the potential to cover about 75% of the total annual electricity consumption on the island (722 MWh/year) by wind energy (25% covered by diesel engine generators), and can at the same time cover 35% of the island's total annual heat demand (2711 MWh/year).

In an actual installation there will be heat losses in the district heating distribution system. These heat losses are not accounted for in this study, but the main results will be about the same: A large amount of otherwise unused wind energy can be captured in a large centralized thermal storage system at Nólsoy.

The next step in the analysis was to see how the results would be affected by changing two of the key system design parameters: (1) The rated wind turbine power ($P_{WECS}$) and (2) the thermal storage volume per household ($V_{DIT}$). Detailed graphical presentations of all of the simulations results are shown in the four figures below. Sensitivity analyses with respect to $P_{WECS}$ and $V_{DIT}$ were performed in order to evaluate the effect on cost of energy (Figure 28), fuel consumption (Figure 29), investment cost (Figure 30), and wind energy utilization (Figure 31).

From Figure 28 it can be observed that the cost of electrical energy is competitive with the cost of energy for the reference wind/diesel system (0.19 €/kWh$_{el}$). The cost of thermal energy is only competitive with the cost energy in an reference oil heating system (0.09 €/kWh$_{th}$) when the rated wind power is greater than 250-300 kW, depending on the size of the thermal storage (100o or 2000 liters per household).

Figure 29 shows how the heating oil consumption is drastically reduced from more than 300 000 liters/year to less than 200 000 liters/year (35% reduction) when the rated wind power is greater than 300 kW. A doubling of the size of the wind turbine to 605 kW will make it possible to reduce the heating oil consumption to less than 100 000 liters/year. In comparison, the diesel fuel consumption, which is around 125 000 liters/year, is only reduced slightly when adding more wind power capacity to the system.

Figure 30 shows that one of the main challenges with building a wind/diesel system with thermal storage and district heating (Figure 26) is the relatively large investment costs, in the order of 0.8 Million € (engineering and civil works not included) for a system with rated wind power of ca. 300 kW. However, a significant reduction in the investment cost can be achieved if a smaller thermal storage system could be designed. In practice, this could be achieved by designing a highly efficient district heating system, where the heat pipes are actively used as part of the thermal energy storage volume. The alternative is to use smaller distributed domestic hot water tanks (DHTs), as discussed above in the Phase II study.

Finally, Figure 31 shows how much of the wind energy can be utilized towards meeting the electrical and thermal energy demands on the island. About 75% of the electrical load can be covered by wind energy in a system with a wind power capacity of 300 kW, while this is only increased to 80% if the wind power capacity is doubled to 605 kW. However, the addition of extra wind power capacity has a significantly positive effect on the system's ability to meet the thermal load, which could be as high as 60-70%, depending on the design of the thermal storage system.

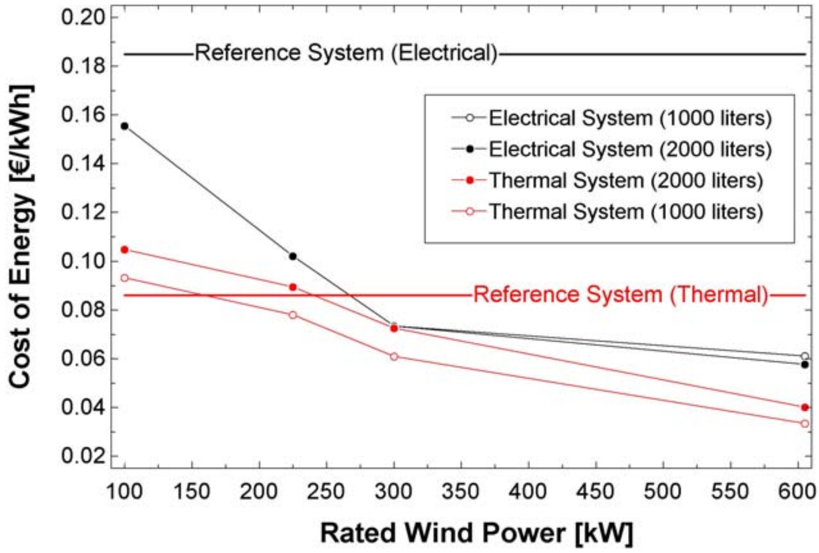


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*Figure 28 Cost of energy (COE) for hybrid WECS/DEGS/DIT-system (Phase III study) as a function of installed wind power capacity (100 – 605 kW) and thermal storage size (1000 or 2000 liters/house).*

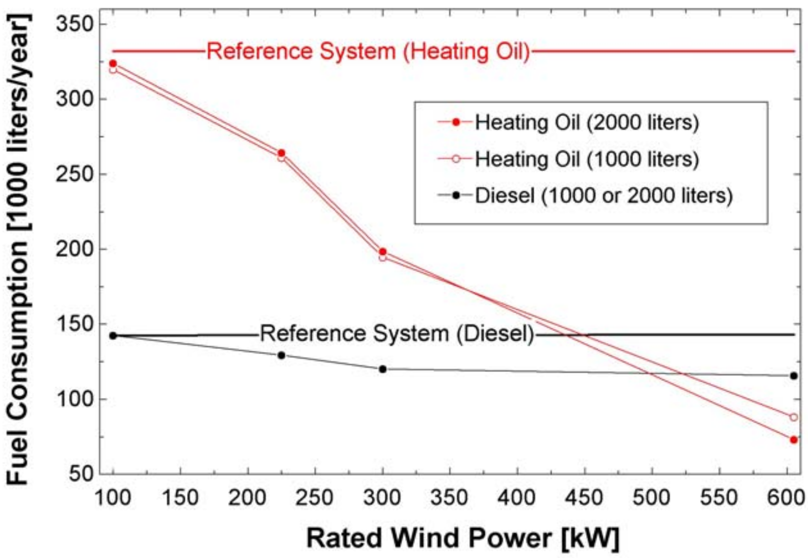


*Figure 29 Fuel consumption (diesel and heating oil) for hybrid WECS/DEGS/DIT-system (Phase III study) as a function of installed wind power capacity (100 – 605 kW) and thermal storage size (1000 or 2000 liters/house)*

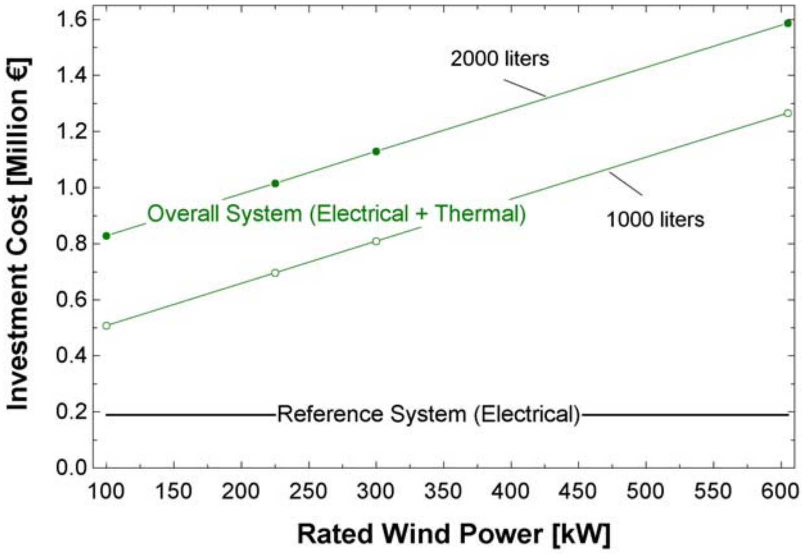


*Figure 30 Investment cost for hybrid WECS/DEGS/DIT-system (Phase III study) as a function of installed wind power capacity (100 – 605 kW) and thermal storage size (1000 or 2000 liters/house).*

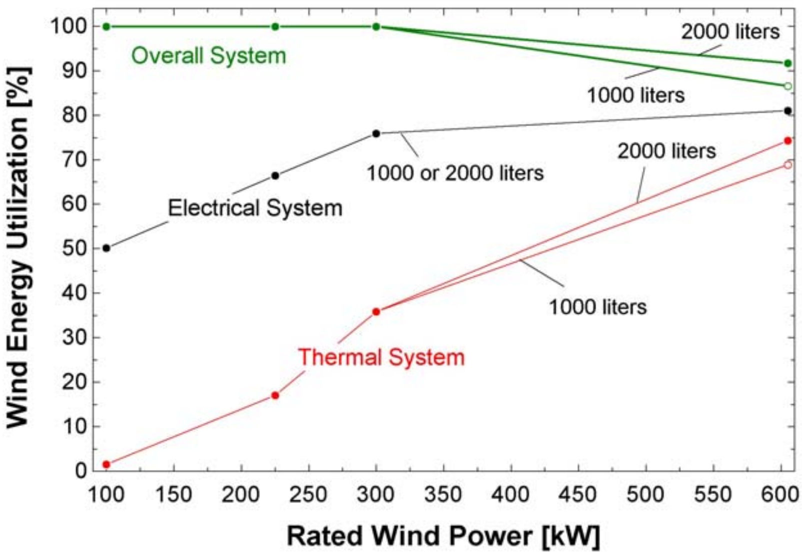


*Figure 31 Wind energy utilization for WECS/DEGS/DIT-system (Phase III study) as a function of installed wind power capacity (100 – 605 kW) and thermal storage size (1000 or 2000 liters/house).*

### 6.3.1 Fossil Fuel Prices – Sensitivity Analysis (Phase III)

A closer look at the WECS/DEGS/DIT-system simulation results described above reveals that about 55-80% of the annual system costs are related to fossil fuel costs (diesel and heating oil), depending on the wind energy utilization and installed wind power capacity (100-605 kW). The cost calculations performed in the Phase III study were based on the following prices:

- Heating oil: 0.70 [€/liter]
- Diesel fuel: 0.80 [€/liter]

These prices represent the typical local prices for diesel fuel and heating oil at Nólsoy. Approximately 16-17 % of the price is value added tax (VAT), while 10-15 % is a petroleum tax. Statistics from the oil suppliers to Nólsoy (Shell and Statoil) showed that prices for diesel fuel and heating oil were highly correlated.

The cost-effectiveness of the overall system is significantly affected by price changes in diesel fuel and heating oil. Hence, a sensitivity analysis on the fossil fuel prices was performed, as shown in Figure 32. The objective here was to find out how a change in fossil fuel price impacts the total annual system cost (investment and operating cost).

The results show that a doubling of the fossil fuel price (Figure 32, Scenario 5) will increase the total annual cost from 300 000 €/year to 540 000 €/year (80% increase) in a system with a 300 kW wind turbine. In comparison, the same system with a 605 kW wind turbine increases the annual costs from 260 000 €/year to 410 000 €/year (60% increase). Hence, it can be concluded that it is more economical with a large 605 kW wind turbine (or possibly 2 × 300 kW wind turbines). Furthermore, the economic advantage of a slightly over-sized wind energy system (605 kW) will be even greater with increasing fuel prices.

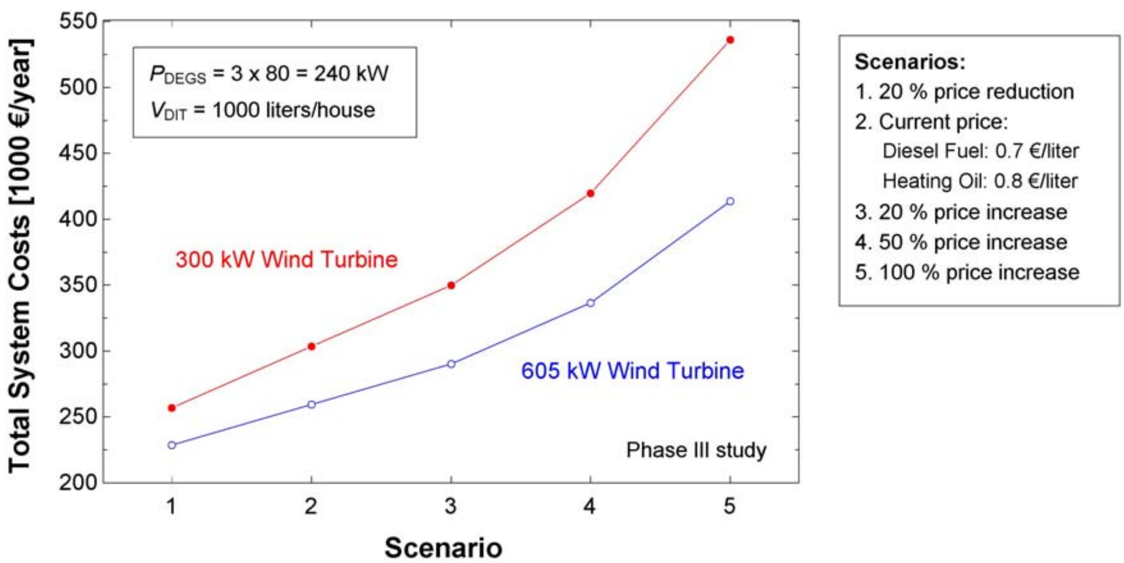


*Figure 32 Total annual system costs as a function of changes in fossil fuel price.*

### 6.3.2 Thermal Storage Characteristics – Sensitivity Analysis (Phase III)

A crucial part of the simulation work performed within Phase III of the West Nordic project was to verify and quality assure the thermal storage model developed for the WECS/DEGS/DIT-system configuration (Figure 26) described and discussed above. Hence, detailed analyses of the dynamic behavior of the thermal storage system were performed, including realistic storage tank temperature control schemes.

The main objective with the work here was to identify a system design with a rated wind power capacity ($P_{WECS}$) and storage volume ($V_{DIT}$) that can provide realistic temperature levels in the thermal storage tank. The method used to evaluate alternative system designs can be illustrated by looking more closely at a week with a relatively high thermal energy demand; the first week in November 2006 was picked as an example. A synthesized thermal demand profile was modeled to represent a combined tap water and space heating demand (ca. 27 000 $kWh_{th}$/year per household, as derived in Phase II study). An example on how this synthesized thermal load profile might look is shown in Figure 33. Typical corresponding temperature profiles for a DIT or DHT-system are shown in Figure 34.

It is important to note that relatively high temperatures are required to meet the local heat demands at Nólsoy, as most of the heat here is intended for use in radiators for space heating or as tap water. In the Phase II study it was found that the so-called *load temperatures* should be about 85 °C for the space heating and 65 °C for tap water heating. In the Phase III study a load temperature set-point of 80 °C was assumed. The importance of having a high load temperature depends on the layout of the final heating system. A centralized district heating (DIT) system with distribution heat pipes will normally require load temperatures in the range 85-90°C (to account for heat losses in the pipes), while distributed domestic hot water tanks (DHTs) typically can get by with temperatures around 70-80 °C. The design load temperature also depends on the local infrastructure in the house (radiators, floor heating, insulation in the walls, etc.)

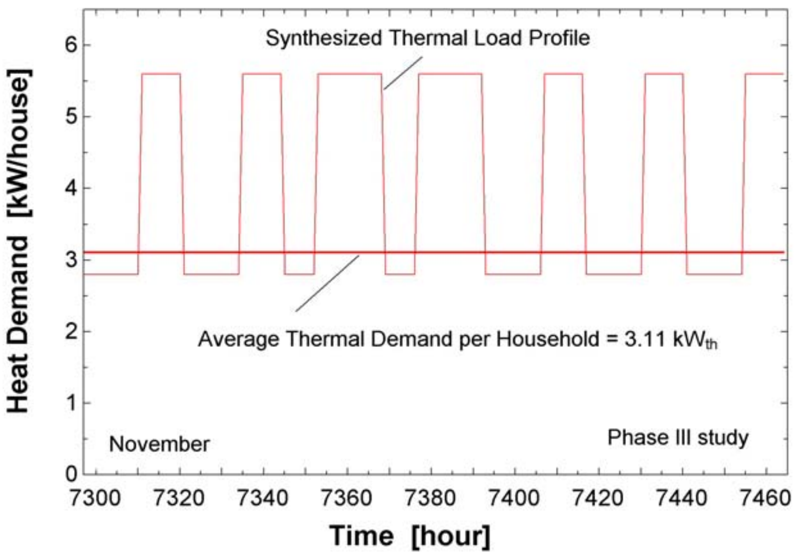


*Figure 33 Synthesized thermal load profile for the first week in November 2006 (Phase III study).*

The thermal dynamic behavior, i.e., load temperature profile, for a WECS/DEGS-system with a large centralized thermal storage tank (DIT) was directly compared to the behavior of a system with distributed small domestic hot water tanks (DHTs), as shown in Figure 34. The main difference in the modeling of these two systems was in the overall heat loss coefficients (slightly smaller for a larger storage tank due to a smaller surface area per volume) and the overall thermal capacities. The differences in heat losses can not easily be deducted from Figure 34, but the difference in thermal capacity can readily be observed by the temperature overshoots, i.e., load temperatures above the set-point temperature of 80 °C. The large storage tank (DIT) is observed to have a more sluggish behavior with larger temperature overshoots (e.g. Figure 34, hour 7310) than the smaller tank (DHT). This is in agreement with standard heat transfer theory.

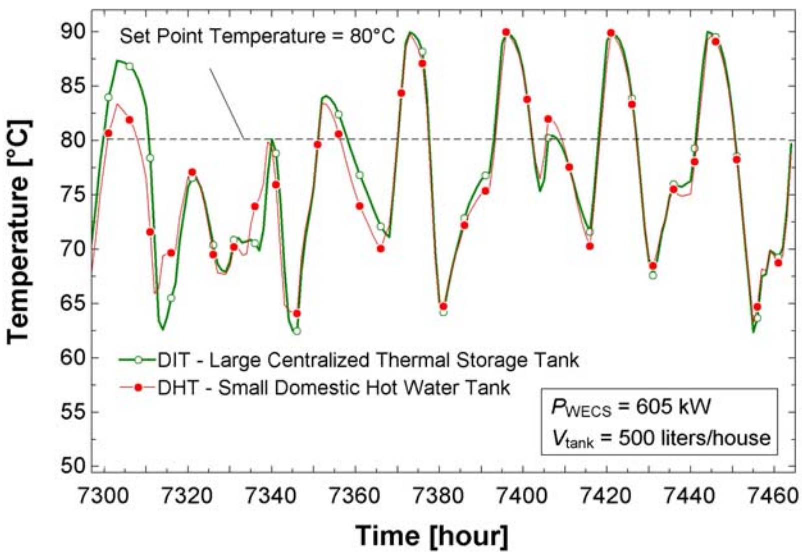


*Figure 34 Comparison of the temperature profile for a large centralized thermal storage tank (DIT) versus the temperature profile for a small domestic hot water tank (DHT) for the first week in November 2006 (Phase III study).*

A closer look at the load temperature profiles for a WECS/DEGS/DIT-systems with different rated wind power capacities ($P_{WECS}$) and storage volumes ($V_{DIT}$) is shown in the four plots in Figure 35. Statistics from the full system simulation runs (15 July – 31 December 2006) are shown in Table 12. The main results can be summarized as follows:

- A large thermal storage volume ($V_{DIT}$) gives a more sluggish behavior with smaller oscillations in temperature (due to large thermal capacity) than a small storage; this results in lower minimum temperatures and higher maximum temperatures.

- An increase in the wind turbine capacity ($P_{WECS}$) from 300 to 605 kW raises the average heat load temperature by approximately 4 °C, from 73°C to 77 °C.

It should be noted here that control of the energy flows and temperatures also affect the thermal behavior of the system. Several alternative control options were investigated in the Phase III study, but these are not discussed in detail in this report.

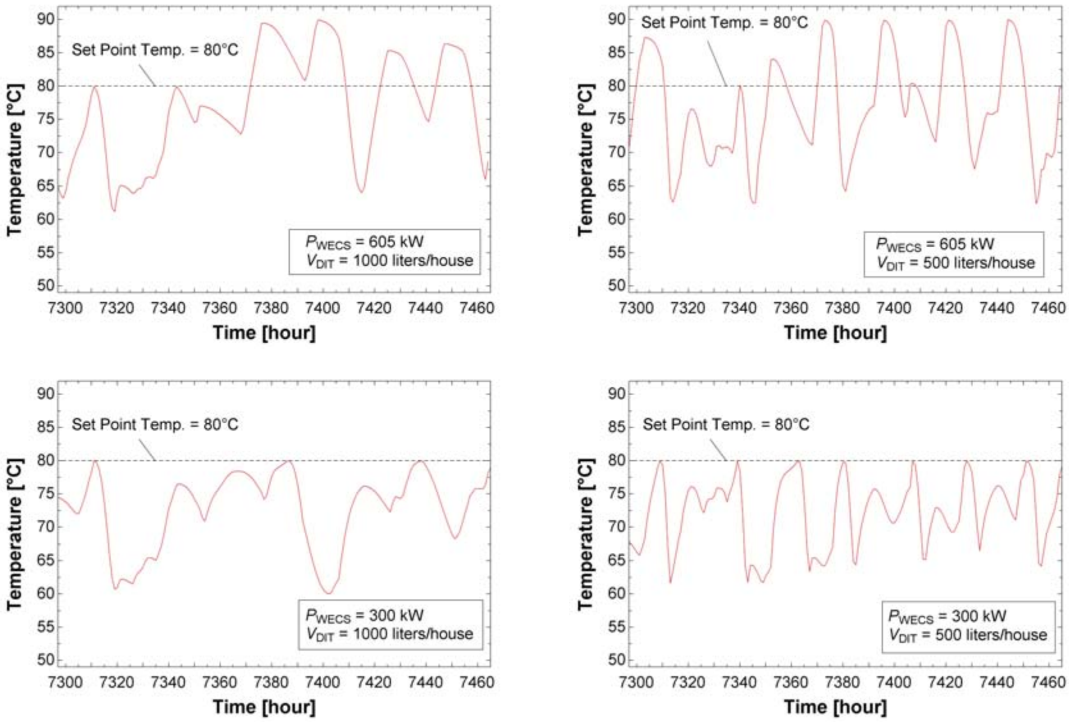


*Figure 35 Temperature profiles for a large centralized thermal storage tank (DIT) for the first week in November 2006. Results are based on unique simulations for various wind power capacities ($P_{WECS}$) and storage tank volumes ($V_{DIT}$).*

*Table 12 Statistics on the temperature profiles generated from DIT and DHT-simulation performed for the period 15 July – 31 December (Phase III study).*

| System Design, # | Wind Power Rating ($P_{WECS}$), kW | Thermal Storage Volume ($V_{tank}$), liters/house | Temperature, °C (Min/Avg/Max) | |
|---|---|---|---|---|
| | | | DIT | DHT |
| 1 | 300 | 500 | 52/73/90 | 53/73/90 |
| 2 | 300 | 1000 | 54/72/86 | 52/72/80 |
| 3 | 605 | 500 | 54/77/90 | 54/76/90 |
| 4 | 605 | 1000 | 56/77/90 | 56/75/90 |

DIT: Large centralized thermal storage tank (district heating)
DHT: Small domestic hot water tank

### 6.3.3 Summary of Results on Wind/Diesel/Heating-Systems (Phase III)

The wind/diesel/heating-system analyses performed in this part of the study demonstrated that it makes sense to include a thermal storage system, both from a technical, economical, and environmental point of view. Detailed system simulation studies were made; the focus was to find an optimal system with respect to wind power ($P_{WECS}$), diesel engine power ($P_{DEGS}$), and thermal storage volume ($V_{DIT}$) capacity. The overall most favorable system configuration had the following design:

- $P_{WECS}$ = 300 kW
- $P_{DEGS}$ = 3 × 80 = 240 kW (more optimal than 2 × 120 kW)
- $V_{DIT}$ = 1000 liters/house

This system design has the potential to cover about 75% of the total annual electricity consumption at Nólsoy (722 MWh/year) by wind energy, while at the same time covering 35% of the island's total annual heat demand (2711 MWh/year). This is a formidable improvement in the overall wind energy utilization compared to the reference wind/diesel-system, which covered "only" 50% of the electrical with wind energy.

The main benefit of adding a thermal storage to a wind/diesel system is that it reduces the cost of electrical energy to 0.07 €/kWh$_{el}$ ($COE_{ref}$ = 0.19 €/kWh$_{el}$). The cost of the thermal energy produced by the system is 0.09 €/kWh$_{th}$, which is slightly higher than the estimated cost of energy for a typical oil heater ($COE_{ref}$ = 0.06 €/kWh$_{th}$). Another significant benefit with the proposed system, at least from a practical point of view, is that it has the potential for significant reductions in fossil fuel consumption. The annual savings in diesel fuel and heating oil was estimated to be 22 000 liters/year and 135 000 liters/year, respectively.

The main disadvantage with the proposed system is the investment cost, which is estimated to be around 1 million €, or more than four times the investment cost of the wind/diesel reference system. For a small island community of a few hundred people, such as Nólsoy, the magnitude of this investment cost can be financially difficult to handle. Hence, it is necessary to find a clever way to finance such an investment. A community-based coop-financing scheme may be a good option (proposed in Phase II study).

The thermal performance of two fundamentally different types of heating systems was investigated in the Phase III study:

1. DIT – A district heating system based on a large centralized thermal storage tank and heat distributed in pipes to each household.
2. DHT – Small domestic hot water tanks located in each household and energy distributed via the local electricity grid.

Sensitivity analyses show that an increase in fossil fuel price makes it favorable to add extra wind power capacity. Hence, if the islanders at Nólsoy want to safe-guard against increased operating costs in the future, due to likely increases in fossil fuel prices, they should actually go for the largest possible wind power capacity ($P_{WECS}$ = 600 kW).

Detailed simulations on the dynamic behavior of various thermal storages shows that it is quite realistic to design a system with suitable heat load temperatures ($T$ = 80±5 °C). The heat load temperature profile for a DIT-system is very similar to that of a DHT-system.

## 6.4 Wind/Diesel-system with Heat and Hydrogen Production (Phase III)

The concept of integrating a hydrogen production, storage, and dispenser system dedicated to a small passenger ferry to/from Nólsoy was introduced early in the project (Phase II study). The overall concept for a wind/diesel-system with district heating and hydrogen production explored in more detail in the Phase III study is shown in Figure 36. In this WECS/DEGS/DIT/$H_2$-system excess energy from the wind turbine is prioritized for use in a water electrolyzer hydrogen production system. The diesel engine generator system was allowed to supply the electrolyzer with idling power at times with low, or no wind. A summary of the main result for the proposed system is provided in Table 13 and Figure 38.

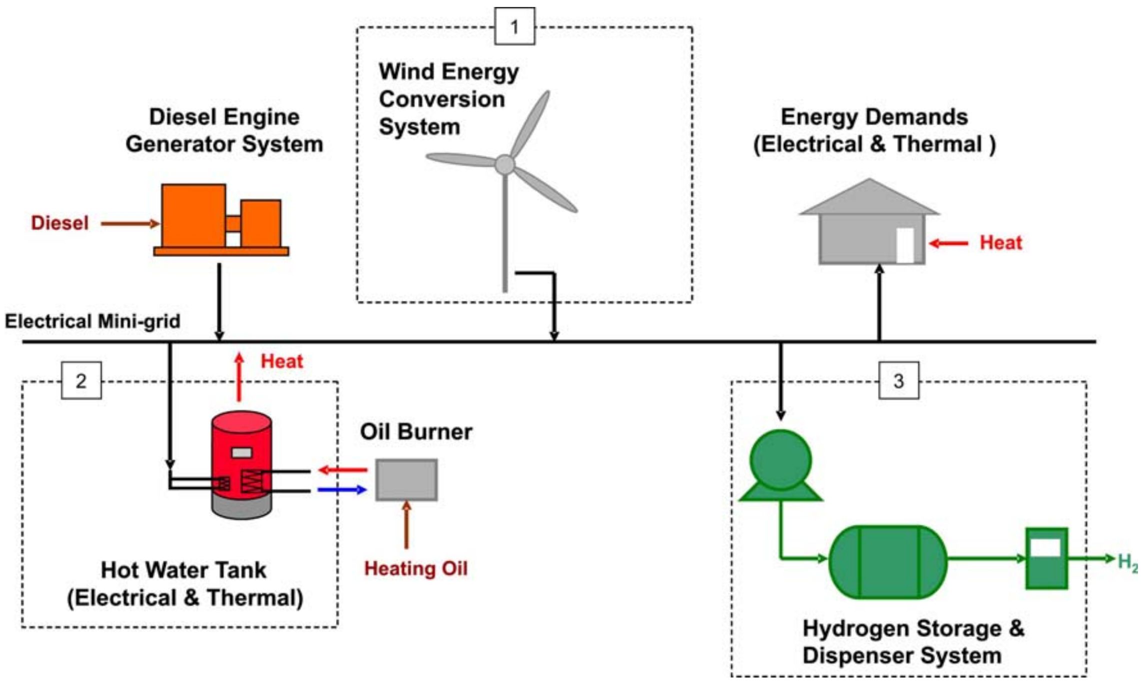


*Figure 36 Wind/diesel-system with district heating and hydrogen production (Phase III study).*

*Table 13 Main results from annual simulation of the WECS/DEGS/DIT/ $H_2$-system (Phase III study). System design: $P_{WECS}$ = 605 kW; $P_{DEGS}$ =3 × 80 = 240 kW; $V_{DIT}$ = 1000 liters/house; $P_{ELY}$ =55 kW (10 $Nm^3$/hour); $V_{H2}$ = 3200 $Nm^3$.*

| System Evaluation Parameter | Specification | Value | Unit |
|---|---|---|---|
| Cost of energy (COE) | Electricity | 0.07 | €/$kWh_{el}$ |
| | Heat | 0.04 | €/$kWh_{th}$ |
| Fossil fuel consumption | Diesel | 117 300 | liters/year |
| | Heating oil | 104 000 | liters/year |
| Investment cost (1) | Overall System | 1.52 | M€ |
| Renewable energy utilization (2) | Electricity | 93 | % |
| | Heat | 63 | % |

(1) Only main system components. Engineering and civil works is not included.
(2) Fraction of wind energy that meets an electrical and/or thermal energy demand.

In the Phase III study two distinct system configurations were analyzed in some more detail, one with a small wind turbine ($P_{WECS}$ = 300 kW) and one with a large wind turbine ($P_{WECS}$ = 605 kW). In both cases, the hydrogen production capacity in the water electrolyzer and storage system was the same ($P_{ELY}$ =55 kW, or 10 $Nm^3$/hour, and $V_{H2}$ = 3200 $Nm^3$). A minimum idling power of 5% of the rated capacity was assumed for the water electrolyzer. The hydrogen storage was designed to capture all of the hydrogen produced over the year; hence, a very large storage was required. The hydrogen consumption at the dispenser was calculated on the basis of synthesized data for a lightweight ferry, with specifications provided in Table 14. I should be noted here that modeling of the hydrogen system was done in a fairly crude way, and that more detailed technical models should be used if the concept proves to be realizable from an economical and practical point of view. It should also be noted here that the investment and operating cost of the hydrogen ferry is not included as part of this study.

*Table 14 Specification of design and operation parameters for the lightweight passenger ferry proposed for commuting between Nólsoy and Torshavn (Phase III study).*

| System Design and Operation Parameters | Value | Unit |
|---|---:|---|
| Fuel cell rated power | 100 | kW |
| Fuel cell idling power | 5 | kW |
| Fuel cell efficiency (electrical) | 50 | % |
| Ferry energy/hydrogen consumption | 1.75 | $kWh_{el}/Nm^3$ |
| Time for roundtrip between Nólsoy and Torshavn | 1 | hour/trip |
| Number of roundtrips per day | 3 | trips/day |
| Daily hydrogen consumption | 170 | $Nm^3$/day |
| Average hourly hydrogen consumption | 7 | $Nm^3$/hour |

The main results from the annual simulations of the WECS/DEGS/DIT/$H_2$-system with a small and large wind turbine ($P_{WECS}$ = 300 kW and $P_{WECS}$ = 605 kW) are shown in the energy flow diagrams in Figure 37 and Figure 38, respectively. In the case with a small wind turbine ($P_{WECS}$ = 300 kW) it is seen that giving priority to hydrogen production leads to a significant increase in the demand for heating oil (Figure 37). In order to maintain a high wind energy utilization on both the electrical and thermal loads, while at the same time producing hydrogen, a large wind turbine ($P_{WECS}$ = 605 kW) must be selected (Figure 38). The alternative is to use a small wind turbine ($P_{WECS}$ = 300 kW) and allow the diesel generator to cover some of the power requirement for the electrolyzer. However, this would mean that about 2-3 % of the hydrogen would be produced by electricity coming indirectly from diesel fuel. This option was not explored in any further detail, as the focus of this study was to design a concept that maximizes the renewable energy utilization.

Finally, year-round consumption of hydrogen produced 100% by renewable energy requires a relatively large hydrogen storage system. The sizing of the hydrogen system is significantly influenced by the excess wind energy available in the system. The final design of a system that takes into account all energy demands (electricity, thermal, and hydrogen) and system operation issues in an economically optimal way is left for future studies.

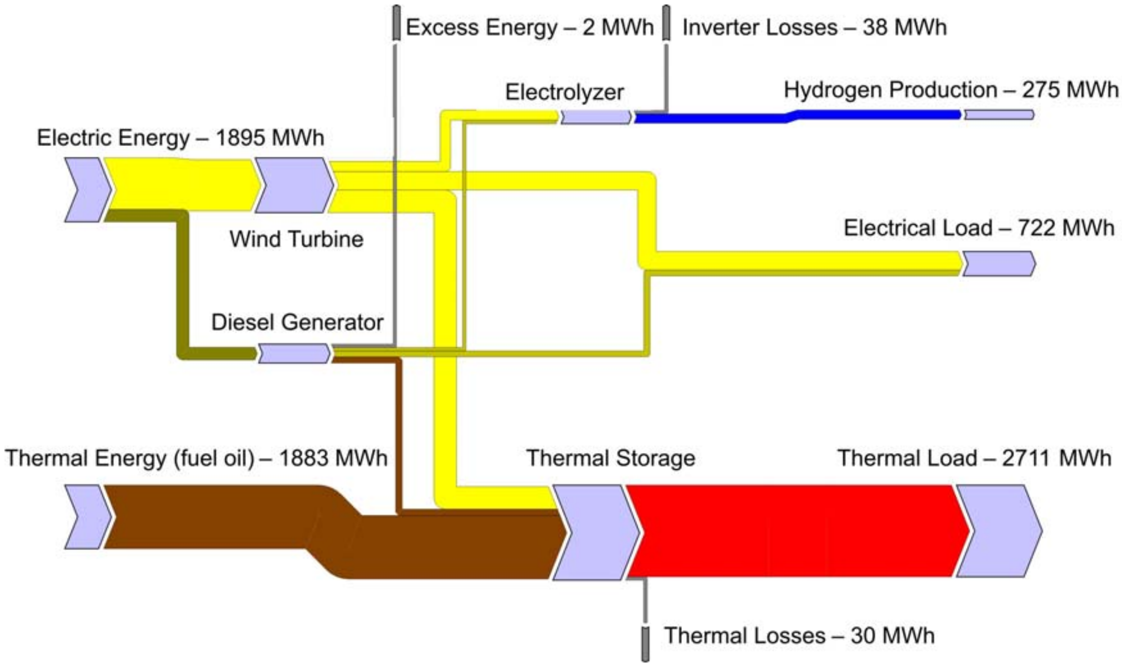


*Figure 37 Energy flow diagram for annual simulation of WECS/DEGS/DIT/$H_2$-system (Phase III study). System design: $P_{WECS}$ = 300 kW; $P_{DEGS}$ =3 × 80 = 240 kW; $V_{DIT}$ = 500 liters/house; $P_{ELY}$ =55 kW (10 $Nm^3$/hour); $V_{H2}$ = 3200 $Nm^3$.*

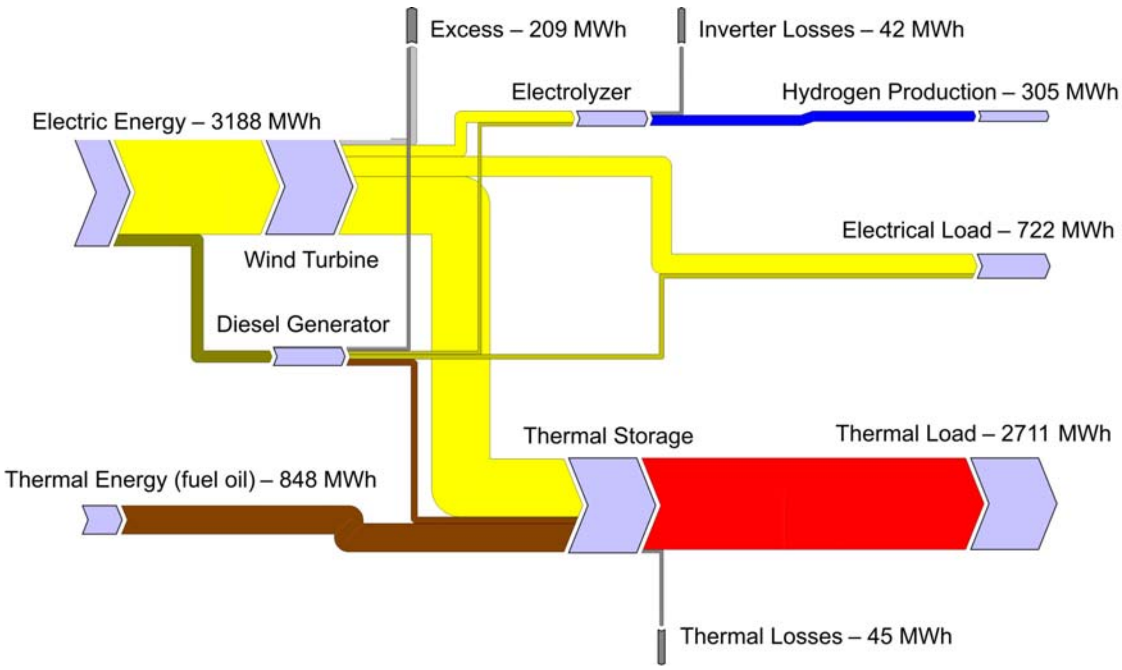


*Figure 38 Energy flow diagram for annual simulation of WECS/DEGS/DIT/ $H_2$-system (Phase III study). System design: $P_{WECS}$ = 605 kW; $P_{DEGS}$ =3 × 80 = 240 kW; $V_{DIT}$ = 1000 liters/house; $P_{ELY}$ =55 kW (10 $Nm^3$/hour); $V_{H2}$ = 3200 $Nm^3$.*

# 7 Conclusions

The objective with the techno-economical system analyses carried out in Phase II and III of West Nordic project was to propose and evaluate renewable energy system concepts suitable for the island of Nólsoy at the Faroe Islands. The overall 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 a thermal storage system tap water and space heating, either via distributed electrical domestic hot water tanks (DHTs) or via a centralized system with heat distribution pipes (DIT).

5. Evaluate the technical and economical potential for installing 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.

## 7.1 Phase II Study

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 for 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 source 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.

## 7.2 Phase III Study

The following work was carried out in Phase III of the project:

- Additional wind speed data for Nólsoy was collected, and a time series for a representative half-year (15 July – 31 December 2006) was developed for use in more detailed system simulations; the time series was based on 10-minute intervals.

- Actual data for the power consumption measured at the transforming station at Nólsoy was collected for the period (15 July – 31 December 2006) and used as basis for the system simulations; the original time series based on 15-minute intervals was converted to 10-minute intervals.

- A more realistic thermal energy demand profile was synthesized; this profile included the wind chill effect on the main building mass (predominantly old non-insulated houses on the island).

- Detailed system simulation based on actual input data (wind speed and electrical load) were performed on three different system concepts:
  1. WECS/DEGS: Wind/diesel-system (reference system, only electricity)
  2. WECS/DEGS/DIT: Wind/diesel-system with thermal storage and district heating
  3. WECS/DEGS/DIT/$H_2$: Wind/diesel with heating and hydrogen production

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

1. The wind conditions at Nólsoy are formidable. The average wind speed at 31 meters above ground for the time period 10 March 2006 – 17 February 2007 was 9.3 m/s.

2. An optimal design for the WECS/DEGS-system was found with respect to rated wind power (300 kW) and diesel power (3 × 80 = 240 kW), based on the wind conditions and electricity demand measured at Nólsoy. This system design resulted in a high renewable energy utilization (50%) and a reasonable cost of energy (0.19 €/$kWh_{el}$), which indicates that Nólsoy is favorable location for wind/diesel systems.

3. An optimal design for a WECS/DEGS/DIT-system was found with respect to wind power (300 kW), diesel engine power (3 × 80 = 240 kW), and thermal storage volume (1000 liters/house). This system has the potential to cover about 75% of the total annual electricity consumption at Nólsoy (722 MWh/year) by wind energy, while at the same time covering 35% of the island's total annual heat demand (2711 MWh/year).

4. The main advantage with a WECS/DEGS/DIT-system is that it significantly reduces the cost of electrical energy (0.07 €/$kWh_{el}$). The cost of the thermal energy produced by the system (0.09 €/$kWh_{th}$) is comparable to that of typical oil heater. Another significant benefit is the potential for annual savings in diesel fuel and heating oil (22 000 liters/year and 135 000 liters/year, respectively). The main disadvantage with a the system is the investment cost (ca. 1 million €, four times the reference system).

5. The dynamic behavior of a WECS/DEGS/DIT-system with a large thermal storage for a district heating solution (DIT) is comparable to the behavior of a system with small domestic hot water tanks (DHTs) distributed in individual household. In both cases it was possible to maintain suitable heat load temperatures (80±5 °C).

6. The results from the WECS/DEGS/DIT/$H_2$-system analyses show that giving priority to hydrogen production can lead to a significant increase in the demand for heating oil (Figure 37), unless the rated wind power capacity is increased (from 300 to 605 kW). Finally, year-round consumption of hydrogen produced 100% by renewable energy requires a relatively large hydrogen storage (3200 $Nm^3$).

# 8 Recommendations for Future Work

For a small island community of a few hundred people, such as Nólsoy, the magnitude of the investment costs calculated in this study can be financially difficult to handle, particularly for the most comprehensive systems (wind/diesel with district heating and hydrogen production). Hence, it is necessary to find a clever way to finance such a long-term investment. A community-based coop-financing scheme may be a good option.

Sensitivity analyses show that an increase in fossil fuel price makes it more favorable to add extra wind power capacity. Hence, if the islanders at Nólsoy want to safe-guard against the increases in fossil fuel prices that are likely to come in the future, they should actually consider investing in a system with the largest possible wind power capacity (600 kW).

The behavior of a system with a large thermal storage for a district heating solution (DIT) is comparable to the behavior of a system with small domestic hot water tanks (DHTs) distributed in individual household. Hence, the decision to invest in a DIT-system versus a DHT-system should mainly be based on what is most practical and economical for the islanders. A DIT-system requires the installation of underground heating pipes, while a DHT-system is likely to require an upgrade of the local electrical grid and the installation of new and more modern hot water tanks in each individual household.

On-site hydrogen production based on excess wind energy system should only be considered if the installation of a large wind turbine (600 kW) can be justified in the first place. The sizing of the hydrogen system is significantly influenced by the excess wind energy available in the system. A more detailed technical study that takes into account all energy demands (electricity, thermal, and hydrogen) and system operation issues in an economically optimal way is recommended.

The following project progress and work stages are recommended for Nólsoy:
1. Perform energy efficiency in the individual homes and other buildings.
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 the 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.

The following project partners are recommended selected for each project stage:
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)

Finally, it should be noted that the methods and simulation tools developed for the Nólsoy case study is directly transferable to similar case studies in the West Nordic region. It is recommended that similar studies are performed for Nanortalik, once the wind and energy demands (thermal and electrical) here have been measured properly. Wind is currently being monitored in Nanortalik, but a proper energy survey has yet to be conducted.

## Acknowledgements

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# Appendix

**Economic Parameters & Cost Functions**

| | Lifetime | Capital Costs fixed | Capital Costs variable | O&M Costs % of investment |
|---|---|---|---|---|
| WECS | 30 [years] | 0 [€] | 1500 [€/kW] | 1.5 [%] |
| PV | 30 [years] | 0 [€] | 6000 [€/kW] | 0.0 [%] |
| Electrolyzer | 20 [years] | 0 [€] | 2000 [€/kW] | 2.0 [%] |
| Fuel Cell | 1 [years] | 0 [€] | 3000 [€/kW] | 2.5 [%] |
| $H_2$-storage | 20 [years] | 2500 [€] | 40 [€/m$^3$] | 0.5 [%] |
| DEGS | 6 [years] | 6000 [€] | 140 [€/kW] | 2.0 [%] |
| HEGS | 6 [years] | 0 [€] | 3000 [€/kW] | 2.0 [%] |
| Heat Pump | 15 [years] | 3300 [€] | 1020 [€/kW] | 3 [%] |
| DHWT | 25 [years] | 0 [€] | 3200 [€/m$^3$] | 3 [%] |

| | |
|---|---|
| Interest rate | 6.00 [%] |
| System Lifetime | 20 [years] |
| Diesel fuel cost | 0.80 [€/L] |
| Fuel Oil cost | 0.7 [€/L] |

WECS = Wind Energy Conversion System
PV = Photovoltaics
DEGS = Diesel Engine Generator System
HEGS = Hydrogen Engine Generator System
DHWT = Domestic Hot Water Tank

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