A comprehensive approach for modelling horizontal diffuse radiation, direct normal irradiance and total tilted solar radiation based on global radiation under Danish climate conditions

A novel combined solar heating plant with flat plate collectors (FPC) and parabolic trough collectors (PTC) was constructed and put into operation in Taars, 30 km north of Aalborg, Denmark in August 2015. To assess the thermal performance of the solar heating plant, global radiation, direct normal irradiance (DNI) and total radiation on the tilted collector plane of the flat plate collector field were measured. To determine the accuracy of the measurements, the calculated solar radiations, including horizontal diffuse radiation, DNI and total tilted solar radiation with seven empirical models, were compared each month based on an hourly time step. In addition, the split of measured global radiation into diffuse and beam radiation based on a model developed by DTU (Technical University of Denmark) and the Reduced Reindl correlation model was investigated. A new method of combining empirical models, only based on measured global radiation, was proposed for estimating hourly total radiation on tilted surfaces. The results showed that the DTU model could be used to calculate diffuse radiation on the horizontal surface, and that the anisotropic models (Perez I and Perez II) were the most accurate for calculation of total radiation on tilted collector surfaces based only on global radiation under Danish climate conditions. The proposed method was used to determine reliable horizontal diffuse radiation, DNI and total tilted radiation with only the measurement of global radiation. Only a small difference compared to measured data, was found. The proposed method was cost-effective and needed fewer measurements to obtain reliable DNI and total radiation on the tilted plane. This method may be extended to other Nordic areas that have similar weather.
A simplified model for linear correlation between annual yield and DNI for parabolic trough collectors

This paper proposes a simple method for estimating annual thermal performance of parabolic trough collectors (PTCs) based on a linear relation with annual DNI for a certain latitude. A case study with simulations for a novel concentrating solar collector in 316 locations for three operating temperature scenarios worldwide was carried out and showed promising results for the latitudes and continents investigated. For a certain latitude and mean operating temperature, the annual yield of a PTC was found to be linearly proportional to yearly DNI. The proposed method will serve as a simplified alternative to the steady-state and quasi-dynamic methods already used. Estimating performance based on yearly DNI can be used by design engineers to do quick preliminary planning of solar plants. Customers can also use this method to evaluate existing solar collector installations. A TRNSYS/TRNSED tool that uses a steady-state model has been developed to carry out the simulations and it has been validated against a PTC array at Technical University of Denmark (DTU). The results show that the simplified method can give reliable estimates of long-term performance of parabolic trough collectors.
The thermal performance of solar collector fields depends mainly on the mean solar collector fluid temperature of the collector field and on the solar radiation. For Danish solar collector fields for district heating the measured yearly thermal performances per collector area varied in the period 2012–2016 between 313 kWh/m² and 577 kWh/m², with averages between 411 kWh/m² and 463 kWh/m². The percentage difference between the highest and lowest measured yearly thermal performance is about 84%. Calculated yearly thermal performances of typically designed large solar collector fields at six different locations in Denmark with measured weather data for the years 2002–2010 vary between 405 kWh/m² collector and 566 kWh/m² collector, if a mean solar collector fluid temperature of 60 °C is assumed. This corresponds to a percentage difference between the highest and lowest calculated yearly thermal performance of about 40%. This variation is caused by different weather conditions from year to year and from location to location. Approximately half of the variations of yearly thermal performances can be related to variable weather conditions.

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Advantages using inlet stratification devices in solar domestic hot water storage tanks

The thermal performance of a domestic hot water system is strongly affected by whether the storage tank is stratified or not. Thermal stratification can be built up in a solar storage tank if the heated water from the solar collectors enters the tank through an inlet stratifier. Measured thermal performances of two solar domestic hot water systems are presented. One system is a traditional high flow system with a heat exchanger spiral in the tank. The other system is a low flow system with an external heat exchanger and a newly developed inlet stratifier from EyeCular Technologies ApS installed in the tank. The two systems are otherwise identical which makes it possible to compare the thermal performance and the thermal stratification built up in each tank. Based on a measuring period of 140 days in the period from April 26, 2016 to September 25, 2016, the investigation shows, that the system with the stratification device has a higher thermal performance compared to the system with the heat exchanger spiral inside the tank. The relative performance (defined as the ratio between the net utilized solar energy of the low flow system and the net utilized solar energy of the high flow system), is a function of the solar fraction. The lower the solar fraction is, the higher the relative performance will be. Weekly relative performances up to about 1.10 are measured. That is, weekly extra thermal performances of up to 10% are measured for the system with the inlet stratifier.

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A numerical model to evaluate the flow distribution in a large solar collector field

This study presents a numerical model to evaluate the flow distribution in a large solar collector field, with solar collectors connected both in series and in parallel. The boundary conditions of the systems, such as flow rate, temperature, fluid type and layout of the collector field can be easily changed in the model. The model was developed in Matlab and the calculated pressure drop and flow distribution were compared with measurements from a solar collector field. A good agreement between model and measurements was found. The model was then used to study the flow distribution in different conditions. Balancing valves proved to be an effective way to achieve uniform flow distribution also in conditions different from those for which the valves were regulated. For small solar collector fields with limited number of collector rows connected in parallel, balancing valves are not strictly necessary if the pressure drop across the collector rows is much higher than the pressure drop along the longest distribution pipe.

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A numerical model to evaluate the flow distribution in large solar collector fields in different operating conditions

A numerical model to evaluate the flow distribution in a large solar collector field was developed in Matlab and is presented in this study. Model and measurements from a solar collector field were compared and a good agreement was found. The model was then used to study the flow distribution in different array layouts. Balancing valves proved to be an effective way to achieve uniform flow distribution also in conditions different from those for which the valves were regulated, as well as in case of irregular layouts with different compositions of the collector rows. A Tichelmann connection gave a uniform flow distribution, especially if the distribution pipe diameter is reduced so to give a constant pressure drop gradient. The reduction in power output from the collector field was approximately proportional to the square of the root-mean-square deviation of the flow distribution, but was generally small, at least under the considered assumptions.

Availability of high quality weather data measurements

In the period 2016-2017 the project “Availability of high quality weather data measurements” is carried out at Department of Civil Engineering at the Technical University of Denmark. The aim of the project is to establish measured high quality weather data which will be easily available for the building energy branch and the solar energy branch in their efforts to achieve energy savings and for researchers and students carrying out projects where measured high quality weather data are needed.

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Thermal stratification built up in hot water tank with different inlet stratifiers

Thermal stratification in a water storage tank can strongly increase the thermal performance of solar heating systems. Thermal stratification can be built up in a storage tank during charge, if the heated water enters through an inlet stratifier. Experiments with a test tank have been carried out in order to elucidate how well thermal stratification is established in the tank with differently designed inlet stratifiers under different controlled laboratory conditions. The investigated inlet stratifiers are from Solvis GmbH & Co KG and EyeCular Technologies ApS. The inlet stratifier from Solvis GmbH is a rigid plastic pipe with holes for each 30 cm. The holes are designed with flaps preventing counter flow into the pipe. The inlet stratifier from EyeCular Technologies ApS is made of a flexible polymer with openings all along the side and in the full length of the stratifier. The flexibility of the stratifier prevents counterflow. The tests have shown that both types of inlet stratifiers had an ability to create stratification in the test tank under the different test conditions. The stratifier from EyeCular Technologies ApS had a better performance at low flows of 1-2 l/min and the stratifier for Solvis GmbH & Co KG had a better performance at 4 l/min. In the intermediate charge test the stratifier from EyeCular Technologies ApS had a better performance in terms of maintaining the thermal stratification in the storage tank while charging with a relative low temperature. [All rights reserved Elsevier].

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Web of Science (2014): Impact factor 3.469
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
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BFI (2012): BFI-level 1
Scopus rating (2012): SJR 1.605 SNIP 2.517 CiteScore 3.65
Web of Science (2012): Impact factor 2.952
Experimental investigations on heat content of supercooled sodium acetate trihydrate by a simple heat loss method

Sodium acetate trihydrate is a phase change material that can be used for long term heat storage in solar heating systems because of its relatively high heat of fusion, a melting temperature of 58 °C and its ability to supercool stable. In practical applications sodium acetate trihydrate tend to suffer from phase separation which is the phenomenon where anhydrous salt settles to the bottom over time. This happens especially in supercooled state. The heat released from the crystallization of supercooled sodium acetate trihydrate with phase separation will be lower than the heat released from sodium acetate trihydrate without phase separation. Possible ways of avoiding or reducing the problem of phase separation were investigated. A wide variety of composites of sodium acetate trihydrate with additives including extra water, thickening agents, solid and liquid polymers have been experimentally investigated by a simple heat loss method. The aim was to find compositions of maximum heat released from the crystallization of supercooled sodium acetate trihydrate samples at ambient temperature. It was found that samples of sodium acetate trihydrate with 0.5–2% (wt.%) Carboxy-Methyl Cellulose, 0.3–0.5 % (wt.%) Xanthan Gum or 1–2% (wt.%) of some solid or liquid polymers as additives had significantly higher heat contents compared to samples of sodium acetate trihydrate suffering from phase separation.

General information

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Experimental investigations on prototype heat storage units utilizing stable supercooling of sodium acetate trihydrate mixtures

Laboratory tests of two heat storage units based on the principle of stable supercooling of sodium acetate trihydrate (SAT) mixtures were carried out. One unit was filled with 199.5 kg of SAT with 9% extra water to avoid phase separation of the incongruently melting salt hydrate. The other unit was filled with 220 kg SAT mixture thickened with 1% carboxymethyl cellulose. The heat exchange capacity rate during the charging of the unit with the extra water was significantly higher than for the unit with the thickening agent due to the different levels of convection. The SAT mixtures in the units were stable and supercooled at indoor ambient temperatures for up to two months, after which the units were discharged. The energy discharged after solidification of the supercooled SAT and water mixture was 194 kJ/kg in the first test cycle, dropping to 179 kJ/kg after 20 test cycles. The energy discharged from the unit with SAT and the thickening agent after solidification was stable at 205 kJ/kg over 6 test cycles.

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Web of Science (2015): Indexed yes
BFI (2014): BFI-level 2
Scopus rating (2014): SJR 3.158 SNIP 3.218 CiteScore 6.93
Web of Science (2014): Impact factor 5.613
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 3.06 SNIP 3.346 CiteScore 6.59
Web of Science (2013): Impact factor 5.261
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Web of Science (2013): Indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 2.778 SNIP 3.076 CiteScore 5.69
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Web of Science (2005): Indexed yes
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Laboratory Testing of Solar Combi System with Compact Long Term PCM Heat Storage

To enable the transition from fossil fuels as a primary heat source for domestic hot water preparation and space heating solar thermal energy has great potential. The heat from the sun has the disadvantage that it is not always available when there is a demand. To solve this mismatch a thermal seasonal storage can be used to store excess heat from the summer to the winter when the demand is higher than the supply. Installing a long term thermal storage in a one family house it needs to be compact and sensible heat storages are not suitable. A latent heat storage with a phase change material (PCM) can provide a more compact way of storing heat. Sodium acetate trihydrate (SAT) is a good candidate material as it has a relatively high heat of fusion and in addition it has the ability to supercool to room temperature without solidifying.

In this paper results from the test of a solar combi system with a latent heat storage with SAT is presented. The SAT heat storage modules were heated to 80 °C by the solar collectors 53 times in the test period from June to November 2015 and this enabled the modules to supercool. Supercooling was achieved for 39 days for a SAT module after which 11 kWh of heat were discharged.
Testing of PCM Heat Storage Modules with Solar Collectors as Heat Source

A latent heat storage based on the phase change material Sodium Acetate Trihydrate (SAT) has been tested as part of a demonstration system. The full heat storage consisted of 4 individual modules each containing about 200 kg of sodium acetate trihydrate with different additives. The aim was to actively utilize the ability of the material to supercool to obtain long storage periods. The modules were charged with solar heat supplied by 22.4 m² evacuated tubular collectors. The investigation showed that it was possible to fully charge one module within a period of 270 minutes with clear skies. In long periods with high level of irradiance several modules were charged in parallel due to the limited heat exchange capacity of the integrated heat exchanger of the modules. After the modules were heated to more than 80°C they were set to passively cool down. Modules reached 30°C in a period of parallel cool down without the sodium acetate trihydrate solidified in 3 of the 4 modules. Further tests showed that stable supercooling at ambient temperature is possible.

Behavior of a solar collector loop during stagnation

A mathematical model simulating the emptying behavior of a pressurized solar collector loop with solar collectors with a good emptying behavior is developed and validated with measured data. The calculated results are in good agreement with the measured results. The developed simulation model is therefore suitable to determine the behavior of a solar collector loop during stagnation. A volume ratio R, which is the ratio of the volume of the vapour in the upper pipes of the solar collector loop during stagnation and the fluid content of solar collectors, is introduced to determine the mass of the collector fluid pushed into the expansion vessel during stagnation, Min. A correlation function for the mass Min and the volume ratio R for solar collector loops is obtained. The function can be used to determine a suitable size of expansion vessels for solar collector loops.
This paper presents an investigation of the differences in modeled thermal performance of solar collectors when meteorological reference years are used as input and when multi-year weather data is used as input.

The investigation has shown that using the Danish reference year based on the period 1975-1990 will result in deviations of up to 39% compared with thermal performance calculated with multi-year the measured weather data. For the newer local reference years based on the period 2001-2010 the maximum deviation becomes 25%.

The investigation further showed an increase in utilization with an increase in global radiation. This means that besides increasing the thermal performance with increasing the solar radiation, the utilization of the solar radiation also becomes better.

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- Web of Science (2013): Indexed yes
Measurements of the angular distribution of diffuse irradiance

Advanced solar resource assessment and forecasting is necessary for optimal solar energy utilization. In order to investigate the short-term resource variability, for instance caused by clouds it is necessary to investigate how clouds affect the solar irradiance, including the angular distribution of the solar irradiance. The investigation is part of the Danish contribution to the taskforce 46 within the International Energy Agency and financed by the Danish Energy Agency. The investigation focuses on the distribution of the diffuse solar irradiance and is based on horizontal measurements of the solar irradiance from 8 different parts of the sky as well as horizontal measurements of the total beam and total diffuse irradiance.

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Scopus rating (2013): SJR 0.42 SNIP 0.778 CiteScore 1.02
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Thermal conductivity enhancement of sodium acetate trihydrate by adding graphite powder and the effect on stability of supercooling

Sodium acetate trihydrate and graphite powder mixtures have been evaluated to investigate the influence of the graphite powder on the stability of supercooling. A sodium acetate and water mixture mixed with graphite powder was successfully supercooled at ambient indoor temperatures for five months. The graphite powder was stabilized using carboxymethyl cellulose and successfully tested in heating and supercooling cycles with no loss of performance. Thermal conductivity enhancing properties of graphite powder was shown in samples.

Since the experiments were conducted in small scale, at 200 g per sample, large scale experiments are required to validate graphite as a thermo conductivity enhancing agent, suitable for use in seasonal heat storage applications utilizing SAT.
In the period 2013-2014 the project “Upgrade and Extension of the Climate Station at DTU Byg” is carried out at DTU Byg. The aim of the project is to renew the hardware and the software for data acquisition and monitoring, exchange cables and cable connections in order to avoid interference of electrical noise from the surroundings and exchange worn out equipment. Further, the aim is to make measured data from the climate station easily available for the users.

**Evaluation of long-term global radiation measurements in Denmark and Sweden**

The climate, especially global radiation is one of the key factors influencing the energy yield of solar energy systems. In connection with planning and optimization of energy efficient buildings and solar energy systems it is important to know the climate data of the area where the buildings/systems are located. This study is based on yearly and monthly values of global radiation based on measurements from a climate station placed on the roof of building 119 at Technical University of Denmark in Kgs. Lyngby, from different Danish climate stations runned by Danish Meteorological Institute and from different Swedish climate stations of Swedish Meteorological and Hydrological Institute. The global horizontal radiation has been measured for a high number of years at all of these stations. The values show a tendency of increased annual global radiation, most likely due to decreased pollution of the atmosphere, increased duration of periods without clouds and/or combination of both these effects.
Twenty years of measurements from a climate station in Lyngby, Denmark show that the global radiation increase is almost 3.5 kWh/m² per year, corresponding to a growth of 7% for the last 20 years. The global radiation variation between the least sunny year to the sunniest year is 22%. Twenty-nine years of measuring of global radiation from twelve radiation stations across Sweden shows an increase of 3.1 kWh/m² per year. The increase is 87 kWh/m², corresponding to 9% of global radiation growth during the last 29 years. The annual global radiation varies between 838 kWh/m²/year in 1998 and 1004 kWh/m²/year in 2002 with an average radiation of 932 kWh/m²/year, corresponding to a radiation variation from the least sunny year to the sunniest year of 20%.

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Solar radiation and thermal performance of solar collectors for Denmark
This report describes the part of the EUDP project “EUDP 11-I, Solar Resource Assessment in Denmark”, which is carried out at Department of Civil Engineering, Technical University of Denmark.

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Solar heating in Greenland: Resource assessment and potential
Solar energy is a clean and natural energy source. The solar radiation on earth – including at Arctic latitudes – is so large that it is possible to utilize solar energy on a large scale. Using solar energy means reducing the use of fossil fuels. The use of solar energy varies from country to country, as does the design of the solar heating systems. The purpose of this study is to investigate the solar radiation potential in Greenland, and to investigate how a solar heating system for Greenland should be designed. In the Arctic several conditions must be taken into account in terms of solar radiation at these latitudes. The sun is positioned low on the sky, which means that the optimum tilt angle of a receiving surface will increase. Also most solar radiation appears in the summertime, where there, at latitudes above the Arctic Circle, is solar radiation 24 hours a day and radiation from all directions. The reflection from the snow will increase the solar radiation on tilted surfaces. The potential of utilizing solar radiation is evaluated based on measurements from several different climate stations in Greenland. An investigation of solar radiation models and their suitability for locations in Greenland is carried out. The investigation analyses the diffuse correlation methods developed by ‘Erbs et al.’ and ‘Orgill and Hollands’. The results show that the two correlations both underestimate the diffuse radiation and overestimate the beam radiation, with ‘Orgill and Hollands’ as the most accurate. Further an investigation of four different radiation models is carried out and shows that they are not suitable for the conditions in Greenland. Of the four models the ‘Liu and Jordan’ model - the simple isotropic model - is the most accurate. In Sisimiut measurements of the total radiation and the ground reflected radiation have been carried out since 2003. This data provides the basis for an investigation of the reflection coefficient for
the ground for periods with and without snow. The measurements show that snow reflects solar radiation like a mirror. The effective albedo is therefore given as a function of the difference between the solar azimuth and the surface azimuth. Equations for the effective albedo is determined for each month of the year based on the measurements, and can be used as input for simulation models. The solar heating systems respectively in the Low Energy House and at the Knud Rasmussen Folk High School in Sisimiut have both provided practical experience of operation and performance of solar heating systems in an Arctic climate. Experience from the installation and repair of the systems showed that trained installers are of vital importance to insure a good performance of the systems. The operation of the solar heating system at the Low Energy House showed that thermosyphoning was a problem during the cold winter months. This is now prevented by a magnetic valve controlled by the pump in the solar collector loop. The system in the Low Energy House has over the course of five years undergone several changes to improve the performance of the system. At present further improvements are still possible regarding utilising the energy from the solar heating system in the space heating loop. The thermal performance of the system at the Knud Rasmussen Folk High School has not reached its optimum potential which is partly due to an electrical error. Measurements from the system have shown that the system is capable of covering most of the hot water consumption for four months during the summer, while also providing energy to the space heating loop. Both systems have pressurised solar collector loops with an expansion vessel, and have proved that this design works well under Arctic conditions, where power-outage is more frequent.

General information
State: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Authors: Dragsted, J. (Intern), Furbo, S. (Intern)
Number of pages: 162
Publication date: May 2011

Publication Information
Place of publication: Kgs. Lyngby, Denmark
Publisher: Technical University of Denmark (DTU)
Original language: Danish
Series: DTU Civil Engineering Report
Number: R-240
ISSN: 1601-2917
Main Research Area: Technical/natural sciences
Electronic versions:
Janne Dragsted - Solar heating in Greenland.pdf
Source: orbit
Source-ID: 313732
Publication: Research › Ph.D. thesis – Annual report year: 2011

Experimental studies on seasonal heat storage based on stable supercooling of a sodium acetate water mixture
Laboratory tests of a 230 l seasonal heat storage module with a sodium acetate water mixture have been carried out. The aim of the tests is to elucidate how best to design a seasonal heat storage based on the salt water mixture, which supercools in a stable way. The module can be a part of a seasonal heat storage, that will be suitable for solar heating systems which can fully cover the yearly heat demand of Danish low energy buildings. The tested module has approximately the dimensions 2020 mm x 1285 mm x 80 mm. The module material is steel and the wall thickness is 2 mm. Different methods to transfer heat to and from the module have been tested. Further, a solidification start method, based on a strong cooling of a small part of the salt water mixture in the module by boiling CO2 in a small brass tank in good thermal contact to the outer side of the module wall, has been tested. Tests of the long term durability of small scale seasonal heat storage modules with different heights have been carried out in order to elucidate the maximum height of a module resulting in a stable heat storage. Based on the studies, recommendations for the design of a seasonal heat storage based on modules with a sodium acetate water mixture will be given.

General information
State: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Authors: Furbo, S. (Intern), Dragsted, J. (Intern), Fan, J. (Intern), Andersen, E. (Intern), Perers, B. (Intern)
Publication date: 2011

Host publication information
Title of host publication: ISES Solar World Congress 2011 Proceedings
ISBN (Print): 978-3-9814659-0-7
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 317022
Publication: Research - peer-review › Article in proceedings – Annual report year: 2011
Pressure and temperature development in solar heating system during stagnation

This paper presents an investigation of stagnation in solar collectors and the effects it will have on the collector loop. At a laboratory test stand at the Technical University of Denmark, a pressurized solar collector loop was designed to test different numbers of collectors and different designs of the pipes of the solar collector loop. During the investigation the pre-pressure of the expansion vessel and system filling pressure was changed. The investigations showed that a large pressurised expansion vessel will protect the collector loop from critically high temperatures as long as the solar collectors have a good emptying behaviour and the circulation pump is turned off during stagnation.

General information
State: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Authors: Dragsted, J. (Intern), Furbo, S. (Intern), Chen, Z. (Intern), Perers, B. (Intern)
Publication date: 2010

Host publication information
Title of host publication: Pressure and temperature development in solar heating system during stagnation
Theoretical study on a solar collector loop during stagnation

A mathematical model simulating the stagnation behavior of a pressurized solar collector loop with solar collectors with a good emptying behavior is developed. Based on the pre-pressure of the expansion vessel, the system filling pressure of the solar collector loop and the design of the solar collector loop, the mass of the fluid flowing into the pressurized expansion vessel and the pressures at the top part and at the bottom part of the solar collector loop during stagnation for the solar collector loop are calculated. The theoretically calculated results are compared with experimental results. There is a good agreement between calculations and measurements. The developed simulation model is therefore suitable to determine the behavior of solar collector loops during stagnation.

General information
State: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Authors: Chen, Z. (Intern), Dragsted, J. (Intern), Furbo, S. (Intern), Perers, B. (Intern)
Publication date: 2010
General information
State: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Authors: Chen, Z. (Intern), Dragsted, J. (Intern), Furbo, S. (Intern), Perers, B. (Intern)
Publication date: 2010
Host publication information
Title of host publication: Thermal advantage of tracking solar collectors under Danish weather conditions
Place of publication: Graz, Austria
ISBN (Print): 978-3-901425-13-4
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 272468
Publication: Research - peer-review › Article in proceedings – Annual report year: 2010

Thermal advantage of tracking solar collectors under Danish weather conditions
Theoretical investigations have been carried out with the aim to elucidate the thermal advantage of tracking solar collectors for different weather conditions in Kgs. Lyngby, Denmark (55.8°N), and for the weather conditions in Sisimiut, Greenland (66.9°N), just north of the arctic circle. The investigations are based on calculations with a newly developed program. Measured weather data from a solar radiation measurement station at Technical University of Denmark in Kgs. Lyngby Denmark in the period 1990 to 2002 and the Danish Design Reference Year, DRY data file are used in the investigations. The weather data used for Sisimiut are based on a Test Reference Year, TRY weather data file. The thermal advantages of different tracking strategies is investigated for two flat plate solar collectors with different efficiencies, operated at different temperature levels. The investigations show that the advantage of full tracking is in the range 40% – 90% depending on the solar collector and the operation conditions. The advantage is higher for a low efficient solar collector than for a high efficient solar collector and higher for high solar collector temperatures than for low solar collector temperatures. Further, design reference years are not suitable to elucidate the advantage by tracking.

Towards seasonal heat storage based on stable super cooling of sodium acetate trihydrate

General information
State: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Authors: Furbo, S. (Intern), Dragsted, J. (Intern), Chen, Z. (Intern), Fan, J. (Intern), Andersen, E. (Intern), Perers, B. (Intern)
Publication date: 2010
Host publication information
Title of host publication: EoroSun 2010 Congress Proceedings
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 272401
Publication: Research - peer-review › Article in proceedings – Annual report year: 2010

Applying measured reflection from the ground to simulations of thermal performance of solar collectors
Solar radiation on tilted and vertical surfaces in the Arctic is, in large parts of the year, strongly influenced by reflection from snow. In connection with planning and optimization of energy efficient buildings and solar energy systems in the Arctic, it is important to have an accurate representation of the reflection from the ground. In this study a more accurate description of the albedo is obtained based on detailed measurements from a solar hat, installed at ASIAQ’s climate station in Sisimiut, Greenland. The solar hat measures the global radiation on horizontal, the total radiation on vertical
surfaces facing north, south, east and west, and radiation reflected from the ground on vertical surfaces facing north, south, east and west. Based on measured data from 2004-2007 the albedo is determined for each month of the year as a function of the difference between the solar azimuth and the azimuth of the surface in question. The paper will present an analysis of simulations of the thermal performance of solar collectors using the standard description of the albedo and using the albedo determined by the measurements. It will be elucidated how important an accurate description of the reflection from the ground is for the thermal performance of solar collectors.

Performance of the Low-energy House in Sisimiut.
A low-energy house was built in Sisimiut, Greenland in 2004-05 and since its inauguration in April 2005, its performance and operation have been object of study for researchers and students. The house is characterised by a highly insulated building envelope, advanced windows and a ventilation system with heat recovery, which should cut the energy consumption of the building to only half of what in 2006 became the permissible value in the Greenlandic building code. In addition to this, the house is equipped with a solar collector that supplies heat to the domestic hot water system and delivers auxiliary heat to a room in the building. The paper briefly introduces the design and technology of the house before reporting on the performance results until date. It has been a challenge in some aspects to introduce new technologies which have not been commonly used before in an Arctic environment, and the paper illustrates some of the experiences in this regard.

A Long Term Test of Differently Designed Evacuated Tubular Collectors
During three years seven differently designed evacuated tubular collectors (ETCs) utilizing solar radiation from all directions have been investigated experimentally. The evacuated tubular solar collectors investigated include one SLL all-glass ETC from Tshinghua Solar Co. Ltd, four heat pipe ETCs and one direct flow ETC from Sunda Technology Co. Ltd and one all-glass ETC with heat pipe from Exoheat AB. The collectors have been investigated side-by-side in an outdoor test facility for a long period. During the measurements, the operating conditions – such as weather conditions and temperature of the inlet fluid to the collectors have been the same for all collectors. The volume flow rate through each of the collectors is adjusted so that the mean solar collector fluid temperature has been the same for all collectors. Thus a direct performance comparison is possible. The side-by-side tests were carried out with different mean solar collector fluid temperatures and in different seasons of the year. The results of the measurements are presented in this paper. The influence of the mean solar collector fluid temperature on the thermal performance of the different collector designs will be discussed. Further, the collector performances are compared for different times of the year and it is illustrated how the performance of the different collector types depends on weather conditions.
Investigation of solar radiation models for high northern latitudes

Performance investigations of differently designed heat-pipe evacuated tubular collectors in the Arctic climate

Solar heating systems in the Arctic
SIDE-BY-SIDE TESTS OF DIFFERENTLY DESIGNED EVACUATED TUBULAR COLLECTORS

Six differently designed evacuated tubular collectors, ETCs, utilizing solar radiation from all directions, have been investigated experimentally. The evacuated tubular solar collectors investigated include one SLL all-glass ETC from Tshinghua Solar Co., four heat pipe ETCs from Sunda Technolgoy Co. and one all-glass ETC with heat pipe from Exoheat AB. The collectors have been investigated side-by-side in an outdoor test facility for a long period. During the measurements, the operating conditions – such as weather conditions, inlet and mean solar collector fluid temperatures have been the same. Thus a direct performance comparison is possible. The results of the measurements will be presented in this paper. Among other things, the influence on the thermal performance of the absorber design will be explained. Further, it will be illustrated how the thermal performances of the different collector types depend on the operating conditions and the time of the year and the collector performances will be compared.

VALIDATION OF SIMULATION MODELS FOR DIFFERENTLY DESIGNED HEAT-PIPE EVACUATED TUBULAR COLLECTORS

Differently designed heat-pipe evacuated tubular collectors have been investigated theoretically and experimentally. The theoretical work has included development of two TRNSYS simulation models for heat-pipe evacuated tubular collectors utilizing solar radiation from all directions. One model is developed for heat-pipe evacuated tubular collectors with flat fins and one model is developed for heat-pipe evacuated tubular collectors with curved fins. The models are characterized by detailed calculations of the heat transfer processes in the fins, by detailed shadow modeling and by fins with selective coating on both sides. The input to the models is thus not a simple collector efficiency expression but the actual collector geometry. In this study, the TRNSYS models are validated with measurements for four differently designed heat-pipe evacuated tubular collectors. The collectors are produced by the Chinese collector manufacturer SUNDA Technology Co. The collectors have either flat or curved fins inside the evacuated tubes, the tubes have different diameters and the fins have selective coating on both sides. The collectors' thermal performances have been measured side-by-side under the same operation conditions in an outdoor test facility. For periods with different operation conditions – such as weather conditions and inlet temperatures – measured and calculated thermal performances are compared for
the four collectors. Further, the measured and calculated dynamic behaviors are compared. In all four cases, a good
degree of similarity between measured and calculated results is found. With these validated models detailed parameter
analyses and collector design optimization are now possible. Key words: Evacuated tubular collector, Heat pipe, Thermal
performance, TRNSYS simulation.

General information
State: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Authors: Fan, J. (Intern), Dragsted, J. (Intern), Furbo, S. (Intern)
Pages: 663-668
Publication date: 2007

Host publication information
Title of host publication: Proceedings of ISES Solar World Congress 2007 : Solar Energy and Human Settlement
Volume: II
Place of publication: Beijing
Publisher: Tsinghua University Press, Springer
ISBN (Print): 978-7-302-16146-2
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 201667
Publication: Research - peer-review › Article in proceedings – Annual report year: 2007

Projects:

IEA SHC Task 55 - Integration of Large SHC Systems into District Heating and Cooling (DHC) Networks (II)
The aim of the project is - through exchange of international knowledge - to develop and promote solar district heating
plants. Denmark is in front in this field and the project gives good opportunities for promotion of Danish know how and
technology. The overall objective is to increase the use of solar thermal energy throughout the world.

Project description
The project activities and expected outcomes are:
System description and design of low cost and high performance large-sized SDH and SDC systems as well as the design
and evaluation of large scale seasonal storages and hybrid technologies.
Further, technical analyses of findings will be presented within a report for city district planners, dealing with the integration
of solar thermal and seasonal storages. Additionally, a specific report for planners will focus on system requirements for
SDH and SDC, modular conception and construction as well as the minimization of piping and losses.
Established business and financing models: Objectives here are reference calculation models of SDH and SDC as well as
economical requirement definitions for new systems and markets.
Guidelines to secure low operation and maintenance efforts for very large systems including automated operational
surveillance.
Advanced control systems for large-sized solar and hybrid systems.
A comparison of measured collector performances in the field, and singular collector tests in the laboratory. Results will be
the basis for a validated measurement method of solar collector fields and the validation of performance guarantee
procedures.
Data for the optimization of very large collector fields’ performances based on adjusted hydraulics and minimized system
losses.
Promotion and technology spread of large systems in new markets through the continuation of the existing database from
the IEA SHC Task 45, 48 and 49.
Country reports including case studies and feasibilities.

Department of Civil Engineering
Energy and Services
Period: 01/01/2019 → 31/12/2020
Number of participants: 7
Large solar heating plants, District heating and cooling, System integration, Solar collector field, Large heat storages,
Performance analysis, Business models, System controls
Acronym: IEA Task 55
Project participant:
Fan, Jianhua (Intern)
Furbo, Simon (Intern)
IEA PVPS Task 16 Solar resource for high penetration
The purpose of this project is to develop better recommendations for understanding the solar energy resource in energy systems with high degree of renewable energy penetration. This is done as a international collaboration within the IEA PVPS programme.

Project description

With increasingly high penetration of PV, concentrating solar power (CSP), and solar heating plants into our energy and heating systems around the world, increased knowledge on the solar radiation potential become ever more important.

During meetings in 2015 and 2016 a detailed work plan was made for an upcoming task in the framework of the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) to address the issues outlined above. The task entitled: “Solar resource for high penetration and large scale applications” was approved by the IEA PVPS Executive Committee in November 2016 as IEA PVPS Task 16. The task runs for three years from 2017 to 2020.

DTU will continue the work done in the IEA SHC Task 46 (2011-2016), where the focus was on the directional and temporal variability of the solar resource. Now the focus will be on how this affects the energy production in the rows of large scale solar collector and PV fields.

Department of Civil Engineering
Energy and Services
Period: 01/01/2018 → 31/12/2020
Number of participants: 6
Solar resource, high penetration renewable energy systems, Solar heating plants, PV, CSP Concentrating solar power
Acronym: IEA Task 16
Project participant:
Fan, Jianhua (Intern)
Furbo, Simon (Intern)
Dragsted, Janne (Intern)
Nielsen, Elsabet Nomonde Noma (Intern)
Perers, Bengt (Intern)
Kong, Weiqiang (Intern)

Financing sources
Source: Public research council
Name of research programme: EUDP
Project

European Committee for Standardization (CEN) Project ECOTEST
This project is funded by European Committee for Standardization (CEN) under the following EU regulations:
Supplementing Directive 2010/30/EU of the European Parliament and of the Council with regards to the energy labelling of space heaters etc.
Supplementing Directive 2010/30/EU of the European Parliament of the Council with regard to the energy labelling of water heaters etc.
The project is focused on evaluation of the standards used and measurement reproducibility of EU laboratories for the application of Ecodesign requirements and labelling of heating and hot water production appliances.
There are eight work packages:
• WP 1 Emissions - CEN/TC 238 (including sound power level)
• WP2 Uncertainty calculation method of the emissions, efficiency and all other parameters and common protocols for the INTER-COMPARISON + uncertainties
• WP3 Ecodesign testing of sanitary hot water work package with CEN/TC 109
• WP4 Work package with CEN/CENELEC JWG FCGA (on mCHP)
• WP5 Work package with CEN/TC 299 (on gas heat pump)
• WP6 Work package with CEN/TC 57 (fuel oil boilers)
• WP7 Work package with CEN/TC 113 (electrical heat pumps)
• WP8 Work package with CEN/TC 312 (solar heaters)

Overall objectives:
1: EVALUATION OF EU LABORATORIES: “to provide for each parameter measured for the application of (EU) No 811/12/13/14 2013 and each appliance a value of the inter-laboratory reproducibility obtained with the test procedures of the corresponding standard developed”
2: EVALUATION OF EU STANDARDS: “to propose improvements of the procedures from the standards”
3: EVALUATION OF EU market surveillance TOLERANCES: “to propose for all parameters and appliances tested a value of a reasonable tolerance that shall be used for the market surveillance”.

Department of Civil Engineering
Energy and Services
Danish Gas Technology Centre A/S
Instytut Nafty I Gazu –Państwowy Instytut Badawczy
KIWA Gastec Netherlands
DVGW-Forschungsstelle EBI
Centre Technique des Industries Aérauliques et Thermiques
IGE-HLK
APPLUS Laboratories
IMQ
KIWA Italy
Technological Centre for the Metal Working Industry
Institute for Solar Technologies SPF
Institute of Thermodynamics and Thermal Engineering ITW
Refrigeration and Heat Pump Technology, Danish Technological Institute
Ait Austrian Institute of Technology GmbH
Wärme-pumpen-Testzentrum Buchs
Fraunhofer Institute for Solar Energy Systems ISE
Politecnico di Milano
TÜV Rheinland Energy GmbH
TÜV SÜD Industrie Service GmbH

Period: 02/10/2017 → 31/12/2018
Number of participants: 5
European Committee for Standardization (CEN), EcoDesign, EU Reference Laboratory, Space heating, Water heaters
Acronym: ECOTEST
Project participant:
Fan, Jianhua (Intern)
Furbo, Simon (Intern)
Nielsen, Elsabet Nomonde Noma (Intern)
Dragsted, Janne (Intern)
Kong, Weiqiang (Intern)

Financing sources
Source: Public research council
Name of research programme: European Committee for Standardization (CEN)
**IEA Task 54 Price reduction of solar thermal systems**
Investigations on solar heating systems with the aim to reduce the price of the systems. Both solar domestic hot water systems and combined systems for space heating and domestic hot water supply are considered.

Department of Civil Engineering
Section for Building Energy

SolarKey Int.
Period: 01/01/2016 → 31/12/2017
Number of participants: 3
Solar heating systems, low flow systems, SDHW systems, Solar combi systems
Acronym: IEA Task 54
Project participant:
Furbo, Simon (Intern)
Perers, Bengt (Intern)
Dragsted, Janne (Intern)

**Superior inlet stratifier**
Development of polymer stratification device, which can establish thermal stratification in hot water stores.

Department of Civil Engineering
Section for Building Physics and Services
Period: 27/10/2014 → 30/06/2015
Number of participants: 4
Thermal stratification, Stratifier, Hot water tank
Project ID: 26407
Project participant:
Furbo, Simon (Intern)
Dragsted, Janne (Intern)
Aagaard, Claus (Intern)
Dandanell, Jens Martin (Intern)

**Off peaking of electricity use for electrical heated energy storages**
Investigations on how to establish temperature stratification in electrical heated tanks with vertical electric heating elements installed at the bottom of the tanks and with a stratification device.

Department of Civil Engineering
Section for Building Physics and Services
METRO THERM A/S
EyeCular Technologies ApS
Period: 30/01/2014 → 31/12/2014
Number of participants: 4
Thermal stratification, Stratifier, Hot water tank
Project participant:
Furbo, Simon (Intern)
Dragsted, Janne (Intern)
Aagaard, Claus (Intern)
Dandanell, Jens Martin (Intern)

**EUDP 12-II, IEA Task 42 Compact Thermal Energy Storage 2. period**
The project is the Danish contribution to the IEA SHC Programme Task 42 project “Compact Energy storage: Material Development and System Integration, 2nd period”.

A seasonal heat storage based on sodium acetate trihydrate with stable supercooling marketed by the German company H.M. Heizkörper GmbH & Co. KG will be evaluated in terms of thermal performance and economy by means of detailed experimental and theoretical investigations.
A seasonal heat storage based on a salt water mixture consisting of sodium acetate and water is currently being developed by Technical University of Denmark, Graz University of Technology, Nilan A/S and Velux A/S in the COMTES project supported by EU. This storage will be compared to the German heat storage.

Calculations of the thermal performance of solar heating systems with the two above mentioned heat stores will be carried out with validated simulation models. The calculations will show how the designs of the solar heating systems including the seasonal heat stores will influence the size of the systems needed to fully cover the yearly heat demand of new buildings.

Based on the calculations and on evaluation of the economic conditions the optimum design and the suitability of the two heat stores will be elucidated.

Department of Civil Engineering
Section for Building Physics and Services
Period: 02/01/2013 → 31/12/2015
Number of participants: 5
Compact seasonal heat storage, PCM, Sodium acetate, Supercooling
Acronym: Task 42
Number of related Ph.D. students: 1
Project participant:
Furbo, Simon (Intern)
Dannemand, Mark (Intern)
Fan, Jianhua (Intern)
Dragsted, Janne (Intern)
Nielsen, Elsabet Nomonde Noma (Intern)

Financing sources
Source: Forskningsprojekter - Miljø- og Energiministeriet
Name of research programme: EUDP
Amount: 2,799,000.00 Danish Kroner
Year of approval: 2012

Relations
Activities:
IEA Task 42 / Annex 29, 12th expert meeting
Project

Advanced Solar Resource Assessment and Forecasting
Detailed measurements and solar radiation models on diffuse radiation from different parts of the sky.

Department of Civil Engineering
Section for Building Physics and Services
Danish Meteorological Institute
Period: 01/09/2012 → 30/09/2015
Number of participants: 3
Acronym: IEA Task 46
Project participant:
Furbo, Simon (Intern)
Dragsted, Janne (Intern)
Nielsen, Elsabet Nomonde Noma (Intern)

Upgrade and extension of the Climate station at DTU Byg
In the period 2013-2014 the project "Upgrade and Extension of the Climate Station at DTU Byg" is carried out at DTU Byg. The aim of the project is to renew the hardware and the software for data acquisition and monitoring, exchange cables and cable connections in order to avoid interference of electrical noise from the surroundings and exchange worn out equipment. Further, the aim is to make measured data from the climate station easily available for the users.

Department of Civil Engineering
Section for Building Physics and Services
Period: 01/08/2012 → 31/10/2014  
Number of participants: 4  
Project ID: 26270  
Project participant: 
Nielsen, Elsabet Nomonde Noma (Intern)  
Dragsted, Janne (Intern)  
Andersen, Lars Kokholm (Intern)  
Kristensen, Troels V. (Intern)  

Financing sources  
Source: Private funding (private)  
Name of research programme: Bjarne Saxhofs Fond  
Amount: 565,200.00 Danish Kroner  
Year of approval: 2012  

Relations  
Publications:  
Upgrade and extension of the climate station at DTU Byg  
Project  

Combined development of compact thermal energy storage technologies  
The aim of the project is to develop a seasonal heat storage consisting of heat storage modules with a salt water mixture of sodium acetate and water. The heat storage concept is based on the advantage of stable supercooling. By using this concept the heat storage module will have no heat loss for a long period making seasonal heat storage possible. If a sodium acetate water mixture, which has a melting point of 58°C, has been fully melted during the sunny summer, it can cool down in its liquid phase to the surrounding temperature and still preserve the latent heat related to the heat of fusion. The heat storage module can be left in this state with no heat loss until a heat demand occurs in the house in the winter, in which case solidification is activated, the heat of fusion is released, and the heat storage temperature increases almost immediately to the melting point.  
The developed heat storage will be a part of a demonstration solar heating system which is intended to cover the total yearly heat demand and hot water consumption of a low energy one family house.

Department of Civil Engineering  
Section for Building Physics and Services  
Technische Universität Graz  
Nilan A/S  
Velux A/S  

Period: 01/04/2012 → 31/03/2016  
Number of participants: 8  
Development, Demonstration, Seasonal heat storage, PCM, Supercooling  
Acronym: COMTES  
Project participant:  
Furbo, Simon (Intern)  
Fan, Jianhua (Intern)  
Dragsted, Janne (Intern)  
Chen, Ziqian (Intern)  
Dannemand, Mark (Intern)  
Nielsen, Elsabet Nomonde Noma (Intern)  
Perers, Bengt (Intern)  
Berg, Jakob Brinkø (Intern)  

Financing sources  
Source: EU research programme (public)  
Name of research programme: seventh framework programme  
Amount: 4,428,000.00 Danish Kroner  
Year of approval: 2012  
Project
Optimal designs for hot water tanks for solar domestic hot water systems
The simulation program MANTLSIM was modified in such a way that the yearly thermal performance of small solar
domestic hot water systems based on mantle tanks was calculated for typical weather conditions for Klagenfurt, Austria.
Calculations of yearly thermal performances for this location were carried out for a solar domestic hot water system with
differently designed mantle tanks. A report with the results of the calculations was worked out.

Section for Building Physics and Services
Department of Civil Engineering
GREENOneTEC Solarindustrie GmbH
Period: 01/08/2011 → 31/12/2011
Number of participants: 4
Project participant:
Nielsen, Elsabet Noma (Intern)
Dragsted, Janne (Intern)
Chen, Ziqian (Intern)
Project Manager, organisational:
Furbo, Simon (Intern)

Financing sources
Source: Sam.arb.aftaler - Udenlandske offentlige og private
Name of research programme: Sam.arb.aftaler - Udenlandske offentlige og private
Amount: 30,800.00 Danish Kroner

Solar Resource Assessment in Denmark, IEA-SHC Task 46
The overall aim of the project is to prepare new solar Design Reference Years, DRYs for different parts of Denmark. The
reference years will be based on measured global radiation from DMI's climate stations. Department of Civil Engineering
will analyse the global and diffuse radiation on horizontal measured for the period 2001-2010 at DTU's climate station at
Kgs. Lyngby. Normal used solar radiation models will be fitted in such a way, that the diffuse radiation on horizontal can be
determined with a good accuracy. These models will be used to determine the diffuse radiation on horizontal for DMI's
climate stations, where only global radiation on horizontal is measured. The developed DRY's will be used to determine
the yearly thermal performance for differently designed solar heating plants. In this way, it will be elucidated how the yearly
thermal performance of solar heating plants is influenced by the design and location of the solar heating plants.

Section for Building Physics and Services
Department of Civil Engineering
Danish Meteorological Institute
Period: 01/07/2011 → 30/09/2012
Number of participants: 2
Project participant:
Dragsted, Janne (Intern)
Project Manager, organisational:
Furbo, Simon (Intern)

Financing sources
Source: Forskningsprojekter - Miljø- og Energi ministeriet
Name of research programme: Forskningsprojekter - Miljø- og Energi ministeriet
Amount: 177,840.00 Danish Kroner

Kvalitetssikring af solvarme, fase 3
Department of Civil Engineering
Period: 01/04/2009 → 31/03/2010
Number of participants: 4
Project participant:
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Climate Change: Adapting to The Impacts, by Communities in Northern Peripheral Regions

Aim
The overall objective of the project is to establish a sustainable advice and training service for community climate change adaptation across the whole of the Northern Periphery. The project, and the eventual information, training, and advice service, will have a particular emphasis on identifying how climate change may bring opportunities for fostering the sustainability of communities in the Northern Periphery through local employment opportunities, social benefits, and environmental management. Participating regions: Scotland - Cairngorms National Park and Glen Urquhart Sweden - Lycksele and Äre Finland - City of Rovaniemi, Kittilä and Kolari Norway - County of Sogn og Fjordane and Flora Greenland - Sisimiut, Ilulissat and Uummanaq

Objectives
The project will undertake a number of key activities over a three-year period, with communities and community sector stakeholders across five regions of the Northern Periphery, to build the necessary knowledge:
- Investigation, collation and communication of relevant information on potential direct and indirect impacts of climate change to small peripheral rural communities;
- Development of adaptation strategies by these communities to avoid or reduce the negative impacts of climate change, while taking advantage of opportunities;
- Implementation of adaptation demonstration projects with a focus on trans-national activities;
- Establishment of a formal mechanism to disseminate knowledge for community adaptation.

Five work packages will jointly contribute to the overall objective. Work packages 2 and 3 will develop the capacity for adaptation, work package 4 will evaluate the realities of delivering adaptation actions, and work package 5 will bring all the lessons together and create a sustainable service, providing information, training and advice relating to community climate change adaptation.

Outcomes
The knowledge gained will initially be made available to all those participating, and then to non-participating communities and stakeholders, through a variety of regional and international dissemination events throughout the project and, in the long term, through the establishment of a formal service. This will ensure a high quality in the content and delivery of information, and the capacity to remain abreast of emerging knowledge relating to climate change, likely impacts, and opportunities for adaptation.
Amount: 1,400,000.00 Danish Kroner
Project

Solvarmeanlæg i Grønland

Department of Civil Engineering
Period: 01/03/2007 → 01/06/2011
Number of participants: 5
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