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Energy Efficiency in Swimming Facilities

Thesis for the degree of Philosophiae Doctor

Trondheim, September 2015

Norwegian University of Science and Technology
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NTNU
Norwegian University of
Science and Technology

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ISBN 978-82-326-0916-1 (print)
ISBN 978-82-326-0917-8 (digital)
ISSN 1503-8181

Doctoral theses at NTNU, 2015:130

Printed by NTNU Grafisk senter

Für meine Eltern

Abstract

High and increasing energy use is a worldwide issue that has been reported and documented in the literature. Various studies have been performed on renewable energy and energy efficiency to counteract this trend. Although using renewable energy sources reduces pollution, improvements in energy efficiency reduce total energy use and protect the environment from further damage. In Europe, 40 % of the total energy use is linked to buildings, making them a main objective concerning reductions in energy use. There are many reports offering possibilities to increase energy efficiency in different building types. However, compared with publications about residential or commercial buildings, few publications have considered sports facilities. This building category contains a variety of different facilities. Among sports facilities, two building types stand out due to their excessive energy use: ice rinks and swimming facilities; this thesis addresses the latter.

The goals of the thesis are as follows:

I Collect energy statistics from swimming facilities in European countries. An in-depth analysis of Norwegian facilities was conducted to compare them with similar facilities in other countries and to define their potential for energy savings.

II Investigate different energy performance indicators (EPI). Few studies have addressed the variety of different indicators for swimming facilities. In addition, there is no consensus in the literature regarding which indicators are best to use.

III Characterise swimming facilities with the lowest energy use. Identify and describe key figures and technologies.

A questionnaire was used to collect data, and answers from 43 Norwegian swimming facilities were used in the analysis. All collected datasets were recalculated to match the Oslo climate in 2010 for better comparison. A significant variation in final annual energy consumption (FAEC) was identified. The potential reduction of the FAEC in Norwegian swimming facilities is estimated to be approximately 28 %.

Correlations between FAEC and the variables of interest were calculated. FAEC was found to have the strongest correlation with water usage (WU), followed by the number of visitors, the usable area (UA) and the water surface (WS). In reality, reliable values for any of these variables are difficult to obtain except for the WS. The author recommends using kWh/visitor as the unit for the EPI if reliable data is available, otherwise kWh/m^2 WS can be used with certain limitations.

Additional data were collected to perform an in-depth analysis. Heat exchangers and heat pumps are used to recover energy from the outgoing water and air in the facilities with the lowest energy use. The energy is then used to warm incoming air, pool water and tap water. The used technology is well known but the composition of the system is decisive. However, even the best swimming facilities have potential for improvement.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfilment of the requirements for the degree of philosophiae doctor.

This doctoral work has been performed at the Department of Civil and Transport Engineering, NTNU, Trondheim, with Amund Bruland as the main supervisor and Bjørn Aas as the co-supervisor.

The work was funded by the Norwegian Ministry of Culture (KUD) and the Centre for Sports Facilities and Technology (SIAT) at NTNU.

When I started in 2009, everything was new, and it took some time to become productive - something very common for PhD students, they told me. When Bjørn started working at SIAT, productivity increased, and I finally had the impression of moving forward. Anyhow, the toughest part was still ahead of me: data collection.

I think collecting data from the field significantly improves my thesis, but it was also challenging. I would even say it was the most time consuming and exhausting part. Insufficient feedback, incorrectly reported data or the missing will or possibility to help were daily companions.

The final part of the process, publishing the papers, was an interesting experience. Sending my work to other experts in the field and awaiting their comments is quite special.

Looking back, this doctoral work was highly fulfilling, and I am very happy to finally defend my work.

Wolfgang Kampel
April 2015, Trondheim, Norway

Acknowledgements

In 2007, I came to Trondheim and undertook an exchange term with the help of the Erasmus program. Due to the help of a friend, I was able to establish contact with the Department of Human Movement Science, who later informed me about this PhD position, which I commenced in 2009.

I was part of the Department for Civil and Transport Engineering, where SIAT was established. I appreciate the help of the centre leader, Bjørn-Åge Berntsen, for his willingness to help and positive attitude. I also have to acknowledge Trine Løkke, who was an important support for me when I started at NTNU.

I also want to acknowledge Mariann Olsen, Daniel Erland, Elin Tønset, Marion Beentjes, Maria Azucena Gutierrez Gonzalez, Sonja Marie Ekrann Hammer and Kjerstina Røhme, who were always available and willing to solve any administrative problems.

My supervisors, Amund Bruland and Bjørn Aas, supported me over the years whenever I asked questions. Amund, with his long experience at the university, and Bjørn, with his experience from industry, were irreplaceable. Without them, I would have much work left to finish my PhD

I was provided an office in the "basement" with many other PhD candidates, which was extremely helpful. I cannot remember any situation where I could not find someone to answer my questions or discuss my results. Furthermore, I want to stress the outstanding social climate. I have made many friends in the basement. I want to thank Daniel Zwick, Sebastian Schafhirt, Mayilvahanan Alagan Chella, Anton Kulyakthin, Eric van Buren, Wenjun Lu, Sergey Kulyakthin, Andrei Tsarau, Ivan Metrikin, Johan Wåhlin, Marat Kashafutdinov, Arun Mulky Kamath, Yangkyun Kim, Nicolas Serre, Raed Lubbad, Torodd Skjerve Nord, Farzad Faridafshin, Marit Reiso, Ole-Christian Ekeberg, Chistian Lønøy, Kenneth Eik, Ada Repetto, Oddgeir Dalane and Vegard Aksnes.

I also have to particularly thank two very important persons. Felix for his healthy attitude, interesting discussions and our many experiences, both in the basement and in and around Trondheim. It would have been a quite different experience without you. Anna for her support whenever needed during the final period of my PhD This was the most intense period of my work, and it was likely not always easy. Thank you for your continuous encouragement and for always being there for me.

I am also very thankful for all of the support from my parents, Josef and Ottilie, and my sister, Eva-Maria. There were almost 2 000 km separating us, but you were always there when I needed you.

Contents

List of Figures

List of Tables

Abbreviations

DE	Delivered energy
ENOVA	Norwegian public company working with more environmentally friendly consumption and generation of energy in Norway
EPI	Energy Performance Indicator
FAEC	Final annual energy consumption
GWh	Gigawatt hours
HDD	Heating degree days
HDD_{17}	Heating degree days with base temperature of 17 °C
HSE	Health, Safety and Environment
HVAC	Heating, Ventilation and Air Conditioning
KUD	The Norwegian Ministry of Culture
kWh	Kilowatt hours
MWh	Megawatt hours
NIVA	Norwegian Institute for Water Research
NOK	Norwegian Krone
NTNU	Norwegian University of Science and Technology
OM	Operation and Maintenance
PE	Primary energy
RH	Relative humidity
SCADA	Supervisory Control and Data Acquisition
SIAT	Centre for Sport Facilities and Technology
UA	Usable area
WHO	World Health Organisation
WS	Water surface area
WU	Water usage
YOH	Yearly operating hours

1 Introduction

1.1 Problem Outline

Worldwide total energy use has been rising over the past few decades. In fact, global energy-use nearly doubled between 1973 and 2011 [1]. The trend of increasing energy use is predicted to continue for the next 30 years [1, 2]. A main cause for greater energy use is population growth and its spin-off effects [3], a trend that is also projected to continue in the coming decades [4]. The effect of population growth is particularly clear when looking at developing countries, where each newborn requires more energy than their predecessors [3].

Initiatives to reduce energy use have been introduced around the world. The EU, for example, set energy targets to be reached in the years 2020, 2030 and 2050 [5]. A major part (40 %) of the total use is related to buildings [6], making them a main target for realising energy savings potential. Many efforts have focused on increasing energy efficiency in different building types, such as residential or commercial buildings.

In Norway, ENOVA offers statistics concerning different types of buildings. A building category that is known to use considerable amounts of energy (Figure 1.1) but has not received considerable attention in the literature is sports facilities. Within this category, swimming facilities and ice rinks are recognised to have the highest energy use [7].

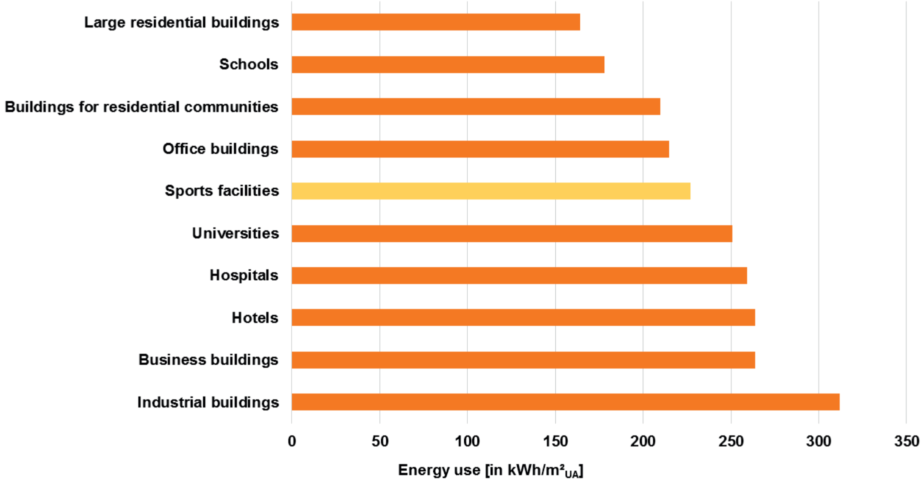

Figure 1.1: *FAEC of the 10 largest building categories in Norway expressed in kWh/m² usable area (UA) [8].*

Norway has approximately 850 swimming facilities [9], which is a noteworthy number in light of the small population. These facilities differ significantly in requirements, use and design. The smallest facilities are typically located in primary schools to teach children how to swim. Facilities for sport and therapeutic use are larger. These larger facilities usually have a lap pool for swimming, a warm water pool for therapeutic purposes and, in some cases, whirlpools, diving platforms or small slides. The largest facilities are often leisure pool facilities with a variety of pools and attractions fulfilling several purposes. Most of the Norwegian swimming facilities are operated by the municipalities, and revenue sources are often limited to ticket sales and other means of income, such as cafeterias and private events. To remain operational, many of the Norwegian swimming facilities are dependent on subsidies from the owner.

The building structures for swimming facilities are designed for their special indoor climate. In addition, the pools require complex technical systems for water purification and climate control. With its complexity and investment in technical equipment, a swimming facility can be better described as a process plant than a building. Several characteristics distinguish swimming facilities from other building categories:

- Temperature and humidity level in the pool room,
- evaporation due to pool usage,
- warm water use for pools and showers,
- presence of a water treatment system,
- energy recovery systems including heat exchangers and heat pumps
- users’ behaviour,
- variety of services provided,
- yearly operating hours (YOH) and their pattern,
- control systems for different process systems and building services, and
- high energy use.

The energy cost is a substantial portion of a swimming facility’s budget. After personnel costs, energy costs are the second largest expense for sports facilities, representing approximately 30 % of the overall operating costs [10]. When evaluating swimming facilities in particular, the relative share of the energy costs increases even more. The major energy demands are related to water heating (for both pools and showers), ventilation, room heating, light systems, the operation of the water treatment system and saunas.

Few studies on specific aspects of swimming facilities have been published [7, 11-14], but the overall approach chosen in the thesis is novel. The studies do not cover all the necessary variables to make a reliable analysis possible. Interpreting the datasets is often problematic, as most of them only present average numbers based on a sample from an entire country. In these cases, information about where the numbers originated or how they were processed is not available. Another common issue is the lack of consensus in the literature about which energy performance indicator (EPI) to use. The two most frequently used EPIs are kWh/m^2_{UA} and kWh/m^2 water surface (WS). This differentiated use makes comparing data from different countries difficult. None of the publications clearly state the reason for choosing a certain EPI.

This thesis covers three different aspects:

- Statistics of Norwegian swimming facilities and their energy use,
- an analysis of EPIs and
- Characteristics of Norwegian swimming facilities with low energy use.

1.2 Research Context

The Norwegian Ministry of Culture (KUD) provides funding for sports facilities (new plants as well as refurbishments) if the project fulfils the criteria set by the Ministry. The Centre for Sport Facilities and Technology (SIAT), within the Department of Civil and Transport Engineering at the Norwegian University of Science and Technology (NTNU), received the assignment to employ a PhD candidate to work with energy efficiency in sports facilities. However, the task to work on all sports facilities within the given time was overly complex. Swimming facilities were selected as the subject of the study because of the significant number of plants in the country and because they use the greatest amount of energy out of all sports facilities [7].

1.3 Research Questions

The initial literature research showed that no complete publication concerning energy use in swimming facilities had been published. Some articles provide average values for an entire country without informing the reader if all swimming facilities are included or only a sample. A distinction between "normal practice" and "good practice" can be found in the literature [14], but there is no information regarding which criteria stands behind these categories.

This thesis discusses which EPI is best to use. In the literature, kWh/m^2_{UA} and kWh/m^2_{WS} are both used to describe energy use, but different authors do not state why they chose the selected EPI. No publications were found to discuss EPIs in swimming facilities.

The literature indicated a large spread in energy use, indicating that some facilities are significantly more energy efficient than others. The third part of this thesis aims to identify and accurately investigate the most energy-efficient swimming facilities.

These existing research gaps led to the following research questions:

RQ1: How is energy use spread when swimming facilities from an entire country are included in the analysis?

RQ2: Is there potential for saving energy in Norwegian swimming facilities, and how large is it?

RQ3: Is there a significant difference between EPIs used to describe the FAEC of swimming facilities?

RQ4: Which variables are adequate for use in the EPI?

RQ5: Which properties are typical for Norwegian swimming facilities with the lowest FAEC?

RQ6: What measures can be applied to improve the energy efficiency of swimming facilities?

1.4 Research Approach

This thesis is mainly based on data collected using questionnaires. The first questionnaire was sent to all Norwegian public swimming facilities. After analysing the data and publishing the first two papers, a second questionnaire was sent to a selection of swimming facilities to obtain the necessary data for the third paper.

1.5 Thesis structure

The thesis is a compilation of the work conducted during the PhD period. It comprises chapters about state of play, applied methods, results, discussion and conclusions. The chapters are based on the papers attached in the Appendix.

Paper I

W. Kampel, B. Aas, A. Bruland, *Energy use in Norwegian swimming halls*, Energy and Buildings, 59 (2013), 181-186.

> **Relevance to the thesis:** This paper addresses RQ1 and RQ2. A questionnaire was sent to all public Norwegian swimming facilities to establish statistics about the FAEC. Extrapolation was then used to calculate the savings potential for the entire building category.
> **My contribution:** This paper is the result of analysing the data collected from questionnaires that were sent to all Norwegian swimming facilities. I was the lead author of the paper.

Paper II

W. Kampel, S. Carlucci, B. Aas, A. Bruland, *Energy performance indicators for a reliable benchmark of swimming facilities*, submitted to Energy and Buildings in April 2015, under review.

Relevance to the thesis: As noted above, no consensus exists in the literature about which EPI to choose for benchmarking swimming facilities. KWh/m$^2_{UA}$ or kWh/m$^2_{WS}$ are typically used. No papers have been published to address this issue. This paper shows different variables influencing the FAEC and that it makes a difference which EPI is used (RQ3). Several variables influencing FAEC were investigated to find the most suitable ones for use in the EPI (RQ4). The authors suggest an EPI to use and justify their choice.

My contribution: This paper is the result of analysing the data collected from questionnaires that were sent to all Norwegian swimming facilities. I was the lead author of the paper.

Paper III

W. Kampel, B. Aas, A. Bruland, *Characteristics of energy efficient swimming facilities*, Energy, 75 (2014), 508-512.

Relevance to the thesis: The most energy-efficient swimming facilities were selected and asked to answer a follow-up questionnaire for a more detailed analysis. The paper shows how the best facilities achieve their low FAEC and provides an overview of possibilities to further reduce FAEC. RQ5 and RQ6 are answered in this paper.

My contribution: This paper is the result of analysing the data collected from the follow-up questionnaires, which were sent to selected swimming facilities. I was the leading author of the paper.

2 The state of play

2.1 Swimming facilities as a building type

The following sections describe the different subsystem of swimming facilities and therewith their differences to residential and commercial buildings.

2.1.1 Building envelope

Because of the special indoor climate in swimming facilities, the building envelope must fulfil special requirements. The main issue is the heat loss through walls, windows and roofs due to the large temperature difference between the indoor and outdoor climates and the high indoor humidity. Condensation is another major problem that occurs on surfaces at a temperature below the dew point. The walls, windows and roof must be designed to avoid conditions below this temperature even on the coldest days of the year [15]. The walls must be as diathermic and vapour-tight as possible on the inside while having the opposite criteria on the outside. The construction should be designed with a U-value that minimises heat loss and avoids condensation. For an outdoor temperature of -20 °C, an indoor temperature of 30 °C and 65 % RH, the U-value must be as low as 0.75 W/m²K to avoid condensation [16]. Achieving this value is rather straightforward for the walls, but windows, doors and thermal bridges represent a challenge. Traditionally, the solution in swimming pool halls has been to introduce air at the floor level below the windows to create a curtain of warm, dry air and avoid humid room air being trapped in cold zones, such as the sill or in the joints between the floor and wall. Special attention must also be paid to thermal bridges [15].

2.1.2 Indoor climate

Compared to office or residential buildings, swimming facilities have a special indoor climate in the poolroom and shower area. The comfort of visitors is mainly influenced by water temperature, air temperature, humidity and air velocity. Typically, the water temperature is in the range of 27 °C (lap pool) to 38 °C (hot tub or Jacuzzi), the air temperature is approximately 30 °C and the relative humidity (RH) is approximately 55 % to 60 % [15]. Variations in evaporation from wet surfaces are the major contributor to climate changes in the room. These variations are caused by the visitors' activity (e.g., waves, splashing in pools, wet floors and wet bodies) and are subject to substantial variations during the day. Measures to keep humidity constant include dehumidification by the use of energy recovery devices or fresh air input. Air quality is also heavily affected by chlorine by-products originating from the pool water. The need for fresh air to dilute the chlorine by-products is an additional design parameter aside from basic human needs. The combination of temperature and humidity creates a high vapour pressure, and the building envelope is exposed accordingly. The combination of a high vapour pressure resistance and good dehumidification measures is mandatory to maintain a healthy building. Thus, the building's energy use is dependent on the selected heating, ventilation and air conditioning (HVAC) system design and building envelope.

Space heating is typically provided by the ventilation system blowing warm air upwards from the floor along the windows. Blowing the warm air on the windows is essential to avoid condensation, which can easily occur because of the higher heat conductivity of glass. Avoiding condensation is of even higher importance in cold countries, such as Norway, where the difference between the inside and outside temperatures can be higher than 50 °C.

2.1.3 Water heating

Swimming facilities have a considerably higher WU than other building categories. Norwegian regulations recommend exchanging 30 l for every visitor per hour if the water is below 34 °C, and 60 l for higher temperatures [17]. Large volumes of water are needed for filter backwash, cleaning the swimming facility and showers. In Norway, hot water is prepared by heating from grid temperature (4 °C to 10 °C) to above 70 °C to kill pathogens [18, 19] and avoid diseases, such as Legionnaires' disease and Pontiac fever. After the heating process, the water is mixed with grid water to achieve the desired water temperature and distributed to showers and taps in the building. Heat recovery from wastewater is essential for energy efficiency because the warm water contains a large amount of energy.

2.1.4 Water treatment

International guidelines concerning water quality are determined in a publication from the World Health Organisation (WHO) [20] and the German standard DIN19643 [21].

Norwegian regulations can be found in the regulations for swimming facilities and sauna (Forskrift for badeanlegg, bassengbad og badstue m.v.) under §16 [22] and the Norwegian Institute for Water Research (NIVA) [23]. The standards provide an overview of the different possible pollution (cosmetics, oil, skin cells, sweat, fat and urine) and their dangers. The most important measures to keep water pollution low are as follows:

- Proper hygiene of the visitors, e.g., taking a shower using soap before entering the pool.
- Replace the recommended amount of water according to the number of visitors.
- Proper operation of the pool water treatment system.
- Keeping the pool facility and pool water clean.

Chlorine is widely used for pool water disinfection. Some swimming facilities partially use seawater, which has the disadvantage of being more corrosive for building materials because it includes approximately 3 % to 4 % NaCl compared to 1 % in chlorine-enriched pool water [17]. Pool water is mainly filtered by sand filters to remove particles. In some newer facilities, activated carbon, UV and membranes are used in addition to the sand filters. The filtering process requires a certain water flow and pressure, provided by the circulation pumps.

2.1.5 Evaporation

Evaporation plays a major role in the design and operation of systems for climate control in swimming facilities. Evaporation is influenced by the size of the wet area, water temperature, air temperature, air humidity and air velocity just above the WS [24, 25]. Consequently, evaporation is closely connected to the number and activity level of visitors in the pool area. With typical climate conditions of 30 °C and 55 % RH, the vapour pressure toward the building envelope is considerable. The pressure may cause severe damage of the building if the envelope is poorly designed or constructed or if the HVAC system is not working properly. Accordingly, the design of the HVAC system and the building envelope is important for maintaining a good indoor climate at the lowest possible energy costs.

2.1.6 Operation and maintenance (O&M)

As noted above, swimming facilities use different technologies to manage the requirements concerning the indoor climate and water treatment. Therefore, employees who are in charge of the operation play a key role. They must maintain the indoor climate to make the visitors feel comfortable while also considering the pool attendants working in the poolroom. Minor changes in temperature can trigger changes in evaporation that lead to higher energy use and higher cost. An even more important issue is water quality; a wrong decision concerning water treatment could lead to health problems of the visitors or the personnel. Understanding the operational data, the technology and the possible settings is of utmost importance.

2.2 Energy use in swimming facilities

Only a few scientific publications can be found concerning energy use in swimming facilities (Figure 2.1). These publications do not include a sufficient amount of data to represent the majority of swimming facilities. One paper provides computed data [26], whereas others take a closer look at a selection of swimming facilities, analysing them accurately with a case study [27, 28].

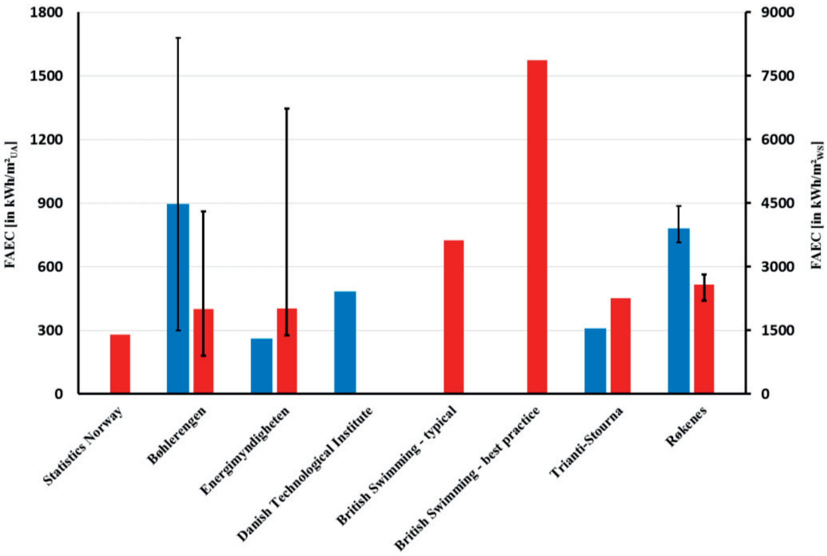

Figure 2.1: *Energy use of swimming facilities in different publications. Values expressed in kWh/m²$_{UA}$ are red and kWh/m²$_{WS}$ are blue.*

More complete studies originate from the public sector in various countries but most of them do not provide any data about the sample the results are based on, making the findings difficult to interpret.

The most comprehensive scientific publication concerning energy use in swimming facilities is from Trianti-Stourna et al. [27] from 1998. The authors state in the introduction that the average FAEC is approximately 4 300 kWh/m^2_{WS} for swimming facilities in Mediterranean climates and that it can reach 5 200 kWh/m^2_{WS} in zones with continental climates, but no scientific background or reference is provided. However, the average FAEC for five case study swimming facilities was shown to be 450.1 kWh/m^2_{UA}. Furthermore, the authors applied a normalising process adjusting for different floor areas, locations, weather conditions, building exposures and operating hours. The resulting EPI varied between 600 kWh/m^2_{WS} and 1 900 kWh/m^2_{WS}.

In a paper from Finland [26], the authors simulated the FAEC to be 636 kWh/m^2_{UA}, which translates into 4 475 kWh/m^2_{WS}. The simulations are based on operating data from a swimming facility in Kirkkonummi. The FAEC expressed in kWh/m^2_{UA} is only 7.5 % higher than that of Trianti-Stourna et al. [27], but there is a large gap between the two publications when expressed in kWh/m^2_{WS}.

Several non-scientific reports were published by the public sectors of various countries. Statistics Norway published a report in 2011 [29] indicating that the average FAEC of 21 Norwegian swimming facilities was 280 kWh/m^2_{UA}. The report did not state whether the included swimming facilities were small school pools, combined sport and leisure facilities or leisure pool facilities. Additionally, no information was provided regarding where these facilities were located, but the authors stated that climate correction was applied to address this issue.

Another source for Norwegian data is the book by Bøhlerengen et al. [16] from 2004. The data from 27 swimming facilities over one year are included, and the FAEC varied from 180 kWh/m^2_{UA} to 860 kWh/m^2_{UA}, with an average of 401 kWh/m^2_{UA}. The numbers are significantly higher than those presented by Statistics Norway.

In an investigation from 2008, the Swedish Energy Agency [7] found that swimming facilities use 403.4 kWh/m$^2_{UA}$ per year, which is similar to the findings from Statistics Norway. The report also expresses the FAEC in kWh/m$^2_{WS}$ and in kWh/operating hour (1 302.7 kWh/m$^2_{WS}$ and 338.8 kWh/YOH). The numbers are based on 17 of the approximately 475 Swedish swimming facilities. No detailed descriptions of the selected swimming facilities are given, but the report does not include school pools or other multi-purpose facilities. The authors stated that swimming facilities have high requirements in terms of maintenance, making well-trained operating personnel a necessity. The variation in FAEC between the facilities is large, confirming the findings in Norway [16]. Most facilities with large WS have a high FAEC, but this fact may not explain the high level of energy use. The potential to reduce FAEC is estimated to be approximately 30 % but is bound to substantial uncertainty.

The British Amateur Swimming Association in their report “Use of Energy in Swimming Pools” [14] differentiates between “good practice” and “typical practice”. No information is provided regarding the sample behind the numbers or the criteria of these two categories. However, the authors state that swimming facilities in the “good practice” category consume 725 kWh/m$^2_{UA}$, whereas those in the “typical practice” category use 1 573 kWh/m$^2_{UA}$. Additional findings showed that the FAEC has decreased for “good practice” swimming facilities between 1996 and 2006, whereas it has increased for “typical practice” swimming facilities in the same period. The values given for both groups are significantly higher than the numbers published by Swedish [7] and Norwegian [29] authorities.

Øen [30] used the same dataset as Bøhlerengen [16] but applied a different EPI (kWh/m$^2_{WS}$). Øen presented values ranging from 1 500 kWh/m$^2_{WS}$ to 8 400 kWh/m$^2_{WS}$ and averaging at 4 481 kWh/m$^2_{WS}$, which is more than three times higher than the figures published from the Swedish Energy Agency [7].

The Danish Technological Institute shows the average FAEC of all Danish swimming facilities varying between 2 291 kWh/m$^2_{WS}$ and 2 608 kWh/m$^2_{WS}$ for 2006 through 2012 [12]. No information is provided regarding how many swimming facilities are included in the sample or if the data are climate corrected. The authors implemented a classification according to size, placing all swimming facilities with 300 m² WS or less into category 1, facilities with 300 m² WS to 600 m² WS into category 2 and those with more than 600 m² WS into category 3.

A free accessible Finnish online database [13] and a German source [11] provide non-climate-corrected raw data from several years, but no public statistics are provided in this dataset.

2.3 Distribution of energy use

As for total energy use, little information has been published concerning energy use for the different subsystems of swimming facilities. Figure 2.2 presents data from four articles that show the distribution of energy use in swimming facilities.

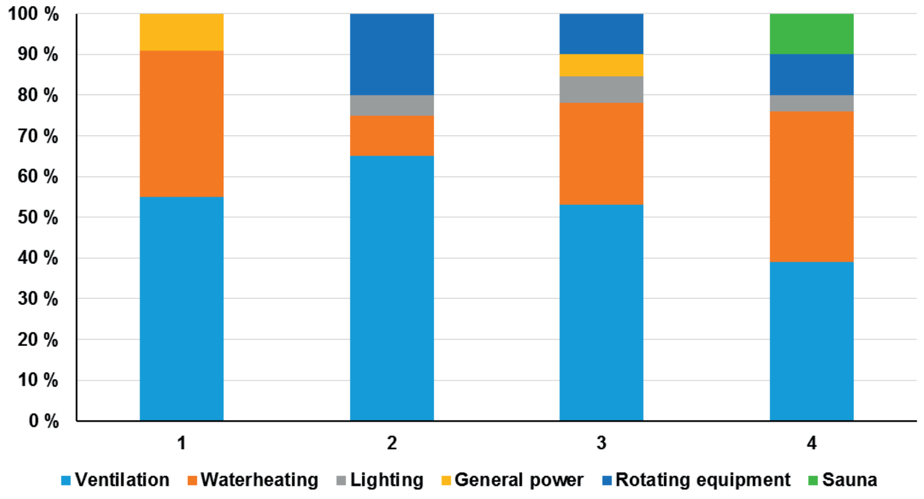

Figure 2.2: *Energy distribution to different subsystems from publications by Trianti-Stourna et al. [27] (1), Røkenes [28] (2), British Swimming Association [14] (3) and Saari and Sekki [26] (4).*

The categories shown in Figure 2.2 group the different terms used in the publications. For example, the publication of the British Swimming Association [14] does not refer to ventilation but to space heating; this term can be assumed to represent the energy used for the ventilation system, including the energy needed for air exchange and evaporation.

Rotating equipment contains technical equipment, fans and pumps. In addition, Røkenes [28] and Saari and Sekki [26] did not measure but computed the distribution of FAEC.

2.4 EPIs

The literature shows that buildings use more energy than necessary because of weaknesses in building design and maintenance [31, 32]. First, the weak points must be made visible to eliminate them [33]. Second, considering the long lifetime of buildings, reliable EPIs are important to describe the facility's state [3].

As Wang et al. [33] state in their publication, benchmarking a building's energy use serves two main purposes: the energy classification and the energy performance diagnosis. Energy classification allows for a comparison of a facility with the sector average or the best-ranked buildings. In contrast, energy performance diagnosis goes into more detail and can be viewed as the second step after energy classification. The energy performance diagnosis is used to identify possibilities for improving the energy efficiency.

To achieve the European climate goals set by the European Union (EU) by 2020, the European Parliament and Council enacted the Directive 2002/91/EC on the energy efficiency of buildings. This directive pledges all member countries to introduce laws for the regulation and energy certification of buildings [34]. Significant EPIs are essential for determining the impact of these policies [33], especially for energy intensive building types [35].

The standard EPI that is used for most building categories is kWh/m^2_{UA}, which is suitable for the residential and commercial sectors. Surprisingly there is little reasoning or discussion why these EPIs are best to use [35]. Another publication by Goldstein & Almaguer [36] state that it is essential that EPIs are meaningful and easy to derive and explain. The EU directive also states that energy use should be combined with the building's designed output to create the EPI [34]. For example, the output of a store in a shopping mall is m^2 selling area, so combining the energy use with the UA is appropriate in this case; the same is true for residential buildings, where the output is m^2 living area.

The output is less clear for sports facilities, especially swimming facilities. No consensus has been reached in the literature, with authors using kWh/m^2_{UA} [14, 16, 28, 29], kWh/m^2_{WS} [12, 27, 30], kWh/m^3 building volume [37] or a mixture of these metrics [7, 28]. The Swedish Energy Agency has used kWh/YOH [7], and Røkenes [28] used kWh/visitors.

None of the authors evaluate or justify their choice of EPI. Energy combined with UA may not accurately represent the energy performance of swimming facilities. The variations in pool design, water attractions, WS, operating hours and visitors must be considered as factors affecting the commonly used EPIs. Comparing small school pools, which are only open during certain periods throughout the year, with leisure pool facilities containing several different pools, water attractions, and relaxation areas is challenging. Furthermore, comparing swimming facilities within a certain group, such as leisure pool facilities, still raises challenges when using UA in the EPI. Major differences are found in the size of entrance areas, technical rooms, and locker rooms, which will distort any comparison or statistical analysis. The requirements of each facility are reflected in the different and complex combinations of HVAC systems, water treatment systems and building envelopes [27]. Using common building EPIs may be less accurate for swimming facilities because of their characteristics:

- Temperature and humidity level in the pool room,
- evaporation due to pool usage,
- warm water use for pools and showers,
- presence of a water treatment system,
- energy recovery systems including heat exchangers and heat pumps
- users’ behaviour,
- variety of services provided,
- yearly operating hours (YOH) and their pattern,
- control systems for different process systems and building services, and
- high energy use.

Because of these characteristics, swimming facilities appear to be better described as process plants rather than buildings, and another methodology should be used to describe their energy performance.

Saygin et al. [38] published a paper about benchmarking process plants in energy-intensive industries. The authors used energy normalised by the output. Pérez-Lombard et al. [39] suggests the same procedure, combining the total energy consumption and output in the EPI, referring to the European Directive 2002/91/EC [40]. For swimming facilities, the output should be measured in annual visitors. The purpose of operation is to make the facility attractive for the public and keep the number of visitors at the highest possible level. However, only one publication [28] was found using kWh/visitors for the EPI to date.

Øen [30] used the data of Bøhlerengen et al. [16] to express FAEC in kWh/m^2_{UA} and kWh/m^2_{WS}. This comparison can be seen in Figure 2.3. Several swimming facilities appear to perform well when expressing FAEC in kWh/m^2_{UA}. However, the same facilities perform rather weakly when FAEC is expressed through kWh/m^2_{WS}. RQ3 aims to investigate this finding.

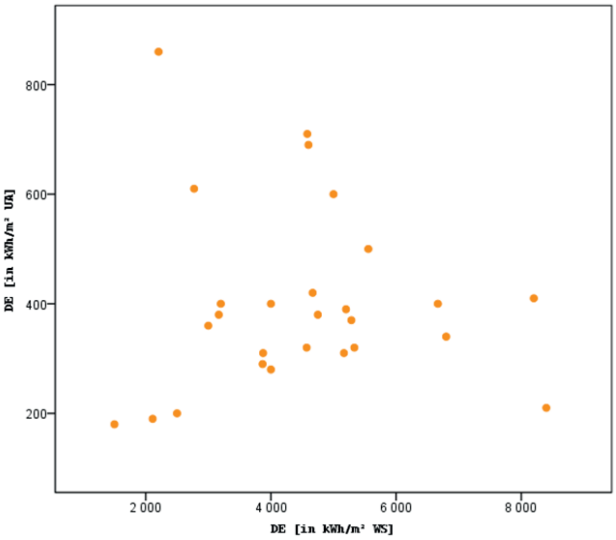

Figure 2.3: *Scatter plot of the FAEC of 27 swimming facilities expressed in kWh/m^2_{UA} (y-axis) and kWh/m^2_{WS} (x-axis). Data from Bøhlerengen et al. [16].*

2.5 Energy savings in swimming facilities

Swimming facilities as a building category differ significantly from other building types in terms of energy use, as described earlier. The large variation can be partially explained by the different types of swimming facilities, variations in age, technology and different maintenance routines, but it also indicates a large energy saving potential.

The case study from Trianti-Stourna et al. [27] investigated five swimming facilities in different parts of Greece. The authors suggested various architectural and electromechanical interventions to reduce energy use. Significant potential for reducing the FAEC was found and presented in the paper. The implementation of different measures was suggested to be decided on a case-by-case basis considering the payback period. The paper also stated that many facilities lack qualified personnel for construction, installation and maintenance processes.

Røkenes [28] confirms that maintenance is critical. The paper found that the largest potential for reducing the FAEC was through an upgrade of the ventilation system, including operational routines, which could reduce the FAEC by 24 %. The next greatest impact was found for installing a heat exchanger for energy recovery, which offered 8 % savings; reducing the U-values of the building envelope only reduced the FAEC by 1 %.

Sun et al. [41] compared a conventional dehumidifier with a heat pump dehumidifier for heating pool water. The conventional dehumidifier was found to recover a sufficient amount of energy to provide the energy needed for water and air heating during summer days when working in heat recovery mode. In autumn, the system covered the necessary heat for the air, but a small part of the energy needed to heat the water would need to be supplied by the auxiliary pool heater. During the winter, a sufficient amount of energy for the air was provided, but the heating of pool water was achieved by the auxiliary pool heater. None of the auxiliary heaters were in use during spring when the system was working in heat pump mode. The authors found that the investment had a payback period of slightly more than one year.

A publication from the ProMidNord project [37] shows implemented measures to reduce energy use in 11 swimming facilities located in Finland, Sweden, Germany, Austria and Portugal. The potential varied, but every swimming facility had room for improvement. Surprisingly, basic actions, such as adjusting the air temperature to be 2 °C higher than the water temperature, were introduced. Many of the measures involved maintenance and operation and were less related to investment in energy saving measures. Applying more comprehensive measures in one case reduced the heat demand by 64 % and the WU by 40 %. The payback time was 8.5 years.

The Carbon Trust [42] suggests using a heat exchanger or heat pumps for the incoming and outgoing air and water. For heat loss due to evaporation, the authors propose pool covers, which were found to reduce the total pool energy use by 10 % to 30 % with a payback period of only 1.5 years to 3 years. The importance of skilled personnel for daily operation and in case of emergency (e.g., trapped visitors under the pool cover) was also addressed.

The Swedish Energy Agency [7] does not present any specific measures to reduce the energy use in swimming facilities, but the authors state that many uncertainties are connected to this building type and that the savings potential could be as high as 30 %.

3 Methods

The following chapter describes the research methods used by the author and how the results of this thesis were obtained.

3.1 Literature review

A scientific literature research serves different purposes [43] where the most important for this thesis were to link the problem to previous work and realise if and what has been done earlier.

Most of the literature was found with the help of web based databases like Engineering Village, Scopus, ScienceDirect and Google Scholar. The search terms were held general to begin with before narrowing them down to find more specific literature. This procedure is in line with the literature search process by Blumberg, Cooper and Schindler [43]. Screening the references of relevant literature often led to finding more relevant publications. Despite that, related literature was obtained directly with the help of the supervisors, which simplified and accelerated the process. Natural limitations for the literature review are the language the documents are published in and documents that slipped through the search.

The literature review did not yield the results the author was hoping for. Especially precise data on the energy use of swimming facilities was scarce.

3.2 Document study

A document study was partly executed in the later stages of the PhD work. Typical documents of interest were manuals and technical specifications of different technologies used in swimming facilities.

Limitations are that these documents do not underlie scientific criteria, that companies might choose to not publish all details about their technology to protect it from their competitors and that there might be some documents that were not found with the document study.

3.3 Survey and case study

After the literature review generated too little data, new data had to be collected from the field. Two possibilities were drafted, a questionnaire or interviews with the people in charge at the swimming facilities. Due to time and financial constraints (travel expenses) the questionnaire was chosen. Yin [44] describes when to use surveys and case studies as research methods. The survey aims at answering the questions who, what, where, how many and how much while case studies go into more detail investigating why certain results occur. The survey was designed with help of current literature [44, 45].

3.4 Data collection

A questionnaire was sent to the 19 Norwegian counties with the request to distribute to their municipalities, who would in turn distribute to each of their swimming facilities. A translated version of the questionnaire can be found in Appendix A.

Initially, a total of 242 datasets from 68 facilities were received, with each facility reporting data for one to ten years. Most of the data were for the years between 2006 and 2010, with the oldest, provided by ENOVA, being from 1998 and the latest, obtained from personal communication after the questionnaire was submitted in early 2011, being from 2011. A single dataset is defined as the FAEC for one year for one facility with the corresponding variables.

More than one third (37 %) of the received data had to be excluded due to inaccuracy, missing data or the lack of energy measuring devices in the facilities. After quality control, 165 datasets from 41 swimming facilities (representing 5 % of the 850 existing facilities in Norway [46]) were included in the analysis concerning energy use.

The questionnaire was designed to cover basic questions about FAEC, including information such as WS, number of visitors, water temperature and WU. The building year of the swimming facilities was acquired from the Norwegian Ministry of Culture database [9]. In cases of important data missing, direct contact via phone or email was established for clarification.

In addition, data were acquired from the Danish Technological Institute [12] for comparison with the Norwegian dataset.

The comparison presented in Paper I includes data from Finland, Greece and Germany that originated from publications by Saari and Sekki [26], Trianti-Stourna et al. [27] and Saunus [15], respectively. The analysis presented in the thesis contains data from Finland [13] and Germany [11] that are raw data edited by the author.

The Finnish database is provided online [13] by the Finnish Ministry of Education and freely accessible. The data included are from 2010 to 2012, when averages were calculated. 98, 71, and 31 swimming facilities reported all of the necessary data for 2010, 2011, and 2012, respectively. German data were acquired from “Deutsche Gesellschaft für das Badewesen e.V.” [11], which include data from 1999 to 2011 and were used to calculate averages for 2009 – 2011.

To answer RQ3 and RQ4, the database was slightly increased through personal communication consisting of 176 datasets from 43 swimming facilities. The variables UA, heating degree days (HDD) and YOH that were not a part of the questionnaire were added.

To investigate RQ5 and RQ6, the most energy-efficient swimming facilities were identified based on the data collected with the questionnaire. To be able to execute a detailed analysis a second questionnaire was designed to collect the necessary additional data. Initially, nine swimming facilities were chosen (three from each category according to WS) to be investigated, but ultimately, six facilities were included in the analysis as data were not available or the operator did not wish to participate in the study. Two versions were sent to the chosen swimming facilities: a printable version and a version to fill out on the computer. The required variables can be seen in a translated version of the questionnaire in Appendix B. Details and uncertainties when analysing the collected data were resolved through personal communication or visits to the facility in question.

3.5 Data processing

The swimming facilities reported data for a different number of years. If sufficient data were available, averages over the last three years were calculated. In this manner, one number was allocated to each facility, giving them the same weight in the analysis. These average values were not used when investigating different EPIs.

The FAEC is defined as the annual delivered energy [47] (in kWh) to each facility. The FAEC values, after being divided by the WS, were used to analyse energy use and when describing characteristics of energy-efficient facilities. The decision to use WS instead of UA in the EPI was mainly made to enable a comparison with Danish data, which is available online [12], and because of uncertainties associated with UA.

Facilities with more than one pool were given a weighted average of the pool temperatures for the overall water temperature.

Subcategories were created, as small school pools cannot be directly compared with significantly larger leisure pool facilities. All facilities have different specifications concerning age, size, building envelope, HVAC system and energy recovery technologies. Because the total number of swimming facilities that reported data was relatively low, the data were not divided into subgroups according to these features. The statistical analysis would be insignificant if an excessive number of categories were created, including too few facilities. However, some categorisation was necessary, so the swimming facilities were divided according to the WS. Facilities with up to 300 m^2 WS were put into category 1, 301 m^2 WS to 600 m^2 WS were put into category 2 and category 3 included the swimming facilities with 601 m^2 WS or more.

The categorisation was slightly altered when investigating RQ5 and RQ6. Swimming facilities with one pool were in category 1, facilities with two or three pools were in category 2 and swimming facilities with more than three pools were in category 3. Although it may seem to be a completely different allocation, the main differences are that small buildings with one pool of 25 m x 12 5 m (312 m²) are in category 1 and some of the facilities with low WS were moved from category 3 to 2.

3.6 Methodological considerations

Analysing energy use and the process of describing characteristics of energy-efficient swimming facilities is mostly descriptive and straightforward. The analysis concerning EPIs needed more methodological considerations where the functional formulation of the problem is:

$$EPI = \frac{Energy\ used}{Normalisation\ metric(s)}$$

The used energy is a function depending on quantities like time period, size of the building, technical systems, services offered, number of visitors etc. Normalisation metrics (also referred to as variables of interest) are quantities that can be measured and explain (even partially) a given performance of the analysed system.

To express energy used (numerator) the most appropriate metric to express the energy performance is DE because the focus is on the system swimming facility including the building envelope and its installations. This choice is also supported by a practical reason as all facilities have a general meter per energy carrier. Therefore, the data can be collected with little effort through on-site measurements and energy bills. DE is defined in European [48] and international standards [49].

Primary energy (PE) is another option and can be used if the system is expanded to assess the source energy footprint of a swimming facility. PE cannot be collected through on-site measurements and strongly depends on "the method used to calculate site-to-source electricity energy factors. National averages do not account for regional electricity generation differences […], for hourly variations in the heat rate of power plants or how utilities dispatch generation facilities for peak loading. Electricity use at night could have fewer source impacts than electricity used during the peak utility time of day" [50].

For the normalisation metrics (denominator), several options exist that have to be tested in order to find the best fit. All variables are described in chapter 3.8.

3.7 Statistical analysis

To present the included variables a univariate analysis was carried out to describe the distribution of each variable stored in the database. They are represented by boxplots (Figure 4.9).

After the Kolmogorov-Smirnov test to check for normality showed that only one variable (water temperature) followed a normal distribution, Spearman's rank correlation was applied. Spearman's method prescinds the data as it uses ranks instead of the absolute numbers. For a better understanding of the spread, scatter plots were created (Figure 4.12).

A multiple linear regression analysis was applied to investigate to what extent the normalisation metrics can explain DE. The non-existence of multicollinearity among the set of independent variables was tested. Because of high correlations between UA, WS, YOH, WU and visitors all but one of these variables had to be excluded. The variable visitors was selected to be pursued in the regression analysis, and the selection process is described in more detail in the discussion. The final model includes DE as dependent variable with Visitors, Age, water temperature and HDD as independent variables. It is based on 101 of the 176 datasets that contain the required variables.

The regression model was then validated with an internal validation procedure. A data-splitting method was adopted, i.e. the original sample was randomly split in two samples. While two thirds (67 datasets) were used to build the model and deviate the regression equation, the remaining third (33 datasets) was utilized to validate the model. The data-split percentage is within the range described by Harrell et al. [51].

3.8 Variables

The following variables will be used throughout the remaining part of the thesis:

- FAEC corresponds to DE for one year as defined in international standards [48, 49].
- UA corresponds to the intra muros area defined in ISO 9836 [52].
- WS equals the pool surface area, where attractions (e.g., slides, sprays etc.) are not included.
- The age of the buildings is an indicator for the technical quality of the building envelope and installed systems' technology. It is defined as Age in the thesis.
- Average water temperature is the average temperature of different pools weighted by their WS. It is abbreviated with AWT in the analyses.
- YOH is defined as the cumulative number of hours when a given facility is in operation in one year.
- Visitors represent the cumulated number of visitors that use a given facility in one year.
- WU is the overall amount of water used in a given facility in one year.
- HDD_{17} refers to HDD calculated with a base temperature of 17 °C [53].

3.9 Climate correction

The datasets used for the analyses concerning energy use and the characteristics of energy-efficient swimming facilities were climate corrected as the data originated from all over Norway, making geographic normalisation necessary. Every dataset was normalised to the 2010 Oslo climate with the degree-days method from ENOVA [54], which is internationally recognised [55]. The degree to which the energy use is influenced by climate depends on the building type. According to ENOVA, this value is as high as 40 % for swimming facilities [56]. The normalising process is based on the degree-days for the corresponding location and year. For the datasets from the different countries the HDD_{17} are available online [57-60]. The base temperature for all degree-days is 17 °C.

The following formula was used:

$$DE_{Oslo} = DE_{actual\ facility}\left((1 - 0.4) + 0.4 * \left(\frac{HDD_{17,Oslo}}{HDD_{17,actual\ facility}}\right)\right)$$

National degree-days were used to correct the data of Danish and German facilities, as the data lacked the specific locations of these facilities.

3.10 Uncertainties

In general, the data collected from Norwegian swimming facilities underwent a process of quality control where extreme values were investigated, corrected if possible and excluded from the analyses if not. The data are subject to human mistakes in reporting the data.

The data collected from Finnish and German swimming facilities include some uncertainty, as no additional information about the facilities was available. For example, some of them could be part of multi-purpose facilities or operate outdoor pools, which could have a significant effect on the data.

The German dataset does not include the locations of the swimming facilities, making a climate correction for every swimming facility impossible. The applied normalisation with the help of HDD_{17} for the entire country can distort the analysis.

Testing the difference of a countrywide climate correction versus climate correction for every facility indicated variations of 1.5 % to 4 % in the three-year average for all Finnish swimming facilities. The included Finnish facilities are spread over the entire country, with a surplus in the south, whereas the distribution of the German data is unknown.

The DE corrected for climate must be viewed as an approximation. In swimming facilities, this value can be expected to differ due to variations in technology and system configuration.

4 Summary of the results

The following chapters present the results of the key aspects. Chapter 4.1 describes the findings for energy use in Norwegian swimming facilities and answers RQ1 and RQ2. An issue that arose during the work for the first paper was the inconsistent use of EPIs, which led to the second paper. The results aiming to answer RQ3 and RQ4 are presented in chapter 4.2. The energy-efficient swimming facilities identified during the work with Paper I were investigated more thoroughly to learn how they have achieved these results. These findings are presented in chapter 4.3, which addresses RQ5 and RQ6.

4.1 Energy use

The paper investigates DE in Norwegian swimming facilities. A main finding, confirming the observations from the literature review, was the large variation in DE. Figure 4.1 depicts the average DE values for the included swimming facilities. DE varies from approximately 1 000 kWh/m²$_{WS}$ to nearly 11 000 kWh/m²$_{WS}$.

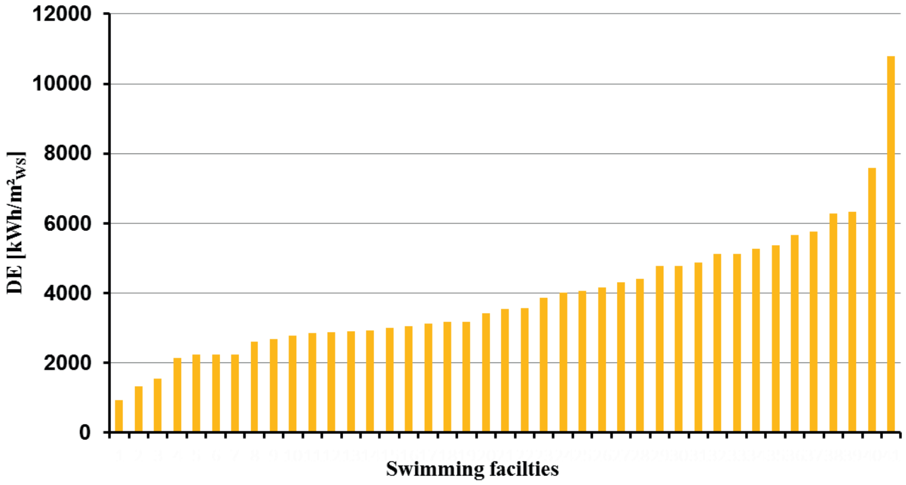

Figure 4.1: *DE (in kWh/m²$_{WS}$, climate corrected) for all included swimming facilities averaged over the reported years and sorted from smallest to largest.*

Different types of swimming facilities have different demands with respect to energy use. Therefore, they were divided into three different categories according to their WS:

- Category 1: Facilities with up to 300 m² WS,
- Category 2: Facilities between 300 m² and 600 m² WS, and
- Category 3: Facilities with more than 600 m² WS.

The average DE per category, with their standard deviation, is shown in Figure 4.2. Category 2 exhibits the lowest DE, whereas the other two categories use nearly the same amount of energy. The standard deviation is high for all categories, reflecting the significant variation in DE in the examined swimming facilities.

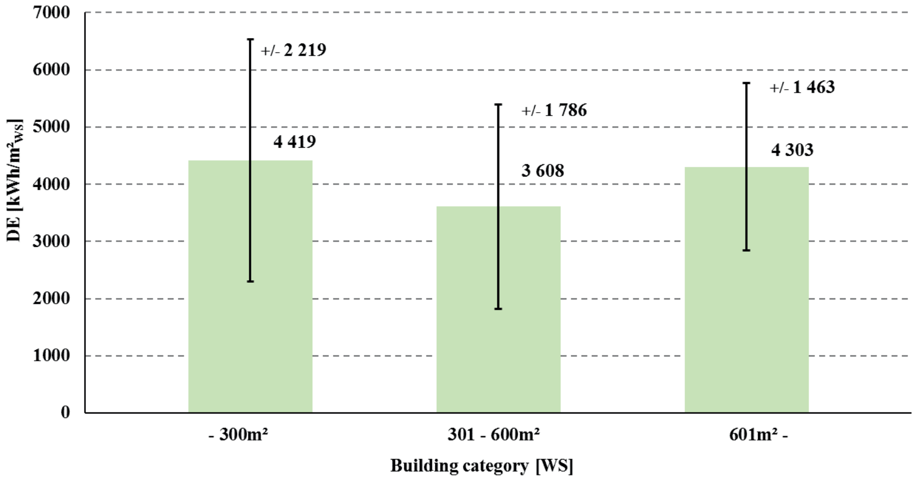

Figure 4.2: *Average DE (in kWh/m²$_{WS}$, climate corrected) per category with standard deviation.*

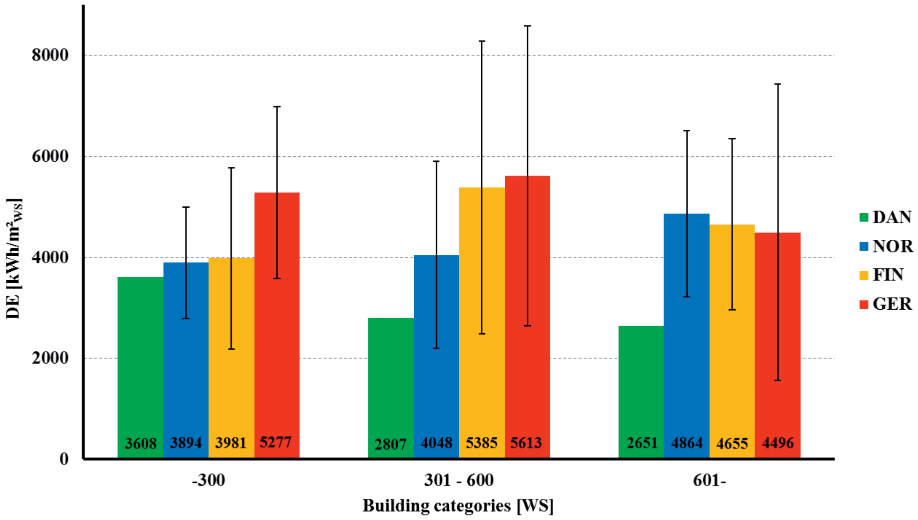

Figure 4.3: *DE (in kWh/m²$_{WS}$, climate corrected) with standard deviation for the investigated countries.*

Data were collected from Norway, Denmark, Germany and Finland and are compared in Figure 4.3. Large standard deviations are found in all countries and categories (Danish data were not available), indicating savings potential.

Another interesting comparison is DE considered by the building year (Figure 4.4). The oldest buildings exhibit the highest DE, and whereas buildings built over the next decade had a considerably lower DE. However, the downward trend does not continue into the following decades. The average DE for each decade varies from approximately 1 000 kWh/m²$_{WS}$ for buildings that were built in the 1960s and later, with the newest buildings showing the highest DE.

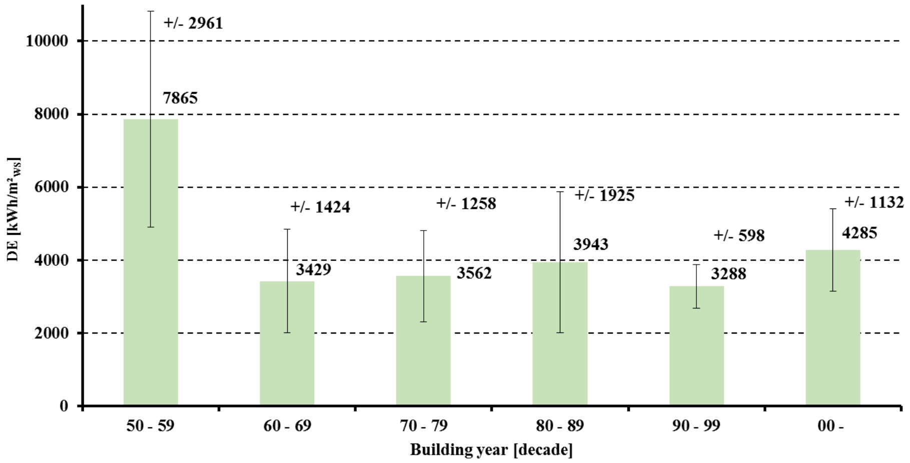

Figure 4.4: *DE (in kWh/m²WS, climate corrected) in relation to building year in decades.*

The varying standard deviation indicates a large savings potential. To determine this savings potential, the average DE of the entire category, the average DE of the better half and the average DE of the best third of each building category were calculated (Figure 4.5).

A substantial difference was found between the total average DE of each category and the corresponding DE of the better half, with a larger difference between the average DE of each category and the average DE of the best third.

In a deeper analysis of the Norwegian data, the buildings in each category were divided into thirds according to DE. These average values are illustrated in Figure 4.6. For the categories of the smallest and medium-sized facilities, the difference between the top and middle thirds is small compared with the gap between the middle and bottom thirds. The columns for the largest category exhibit a more homogenous distribution, where the gaps between the thirds are nearly equal.

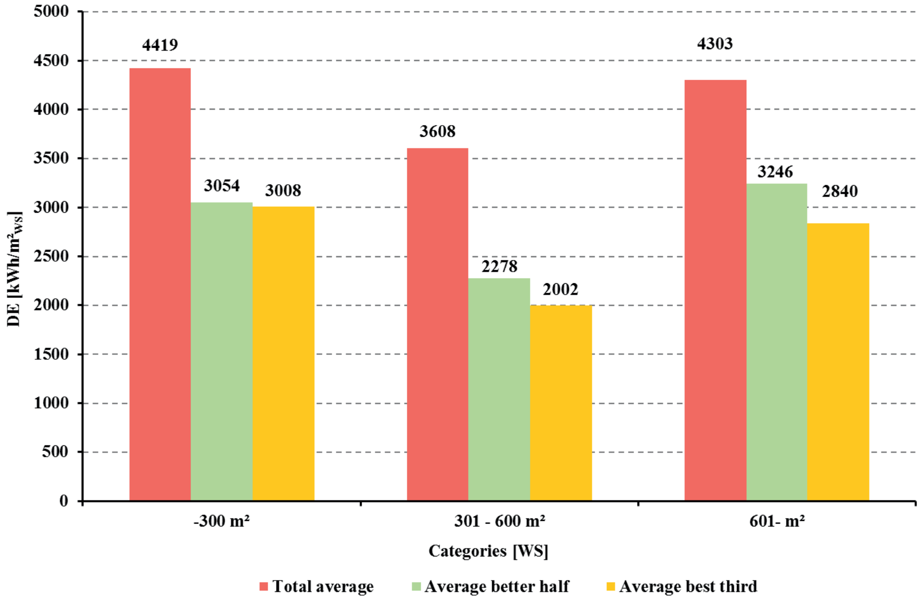

Figure 4.5: *Average of the total (red), the better half (green) and the best third (orange) of DE (in kWh/m²$_{WS}$, climate corrected) in Norwegian swimming halls, per category.*

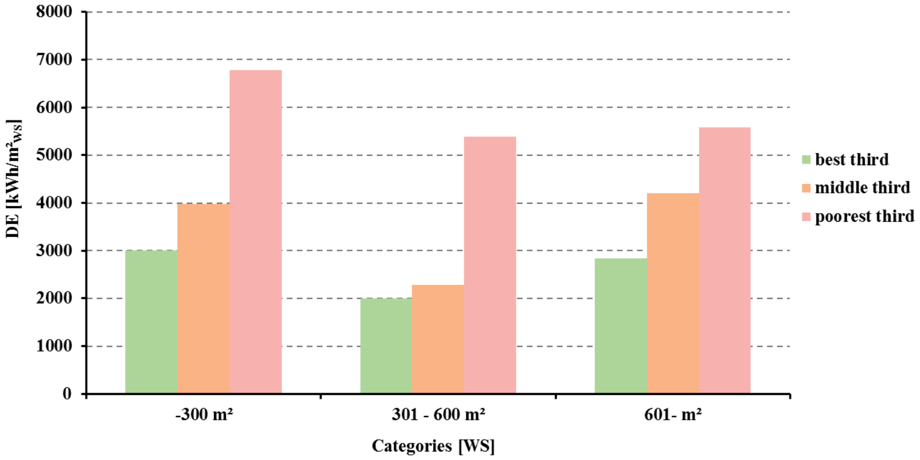

Figure 4.6: *Average DE (in kWh/m²$_{WS}$, climate corrected) of the top (green), middle (orange) and bottom thirds (red) of the different categories.*

The second method for determining savings potential was to compare the Norwegian and Danish data (Figure 4.7).

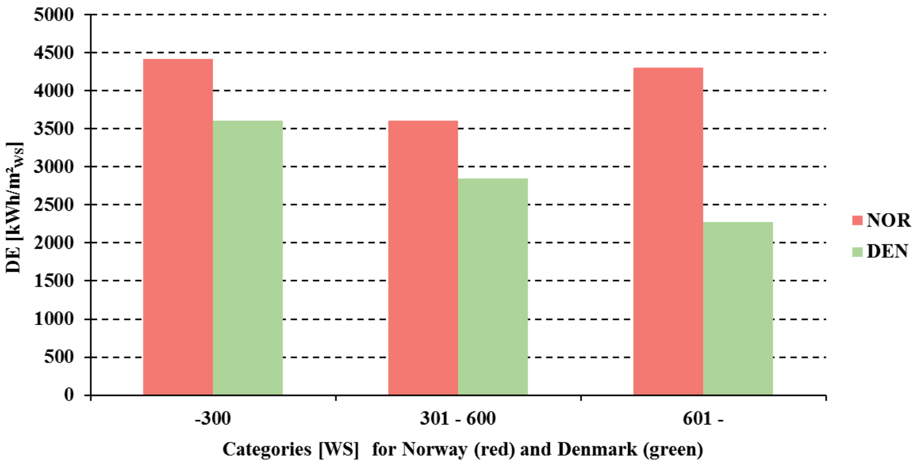

Figure 4.7: *Comparison between Norway (red) and Denmark (green) in terms of DE (in kWh/m$^2_{WS}$, climate corrected) per category.*

Norwegian facilities in categories 1 and 2 consume approximately 1 000 kWh/m$^2_{WS}$ more than their Danish counterparts. Category 3 exhibits the largest difference between the two countries, with Danish facilities using approximately half the energy of the Norwegian facilities.

Table 4.1: *Potential for energy efficiency improvement in Norwegian swimming facilities.*

	-300 m^2	301 - 600 m^2	601- m^2
Total average	4419	3608	4303
Average better half	3054	2278	3246
% difference to total	-31	-37	-25
Danish average	3611	2847	2276
% difference to total	-18	-21	-47
Estimated savings percentage	-25	-29	-36
Estimated savings per facility	1087	1046	1542
Number of facilities	550	278	22
Savings in GWh	91	120	38

To calculate the savings potential, the difference between the average DE and the DE of the better half in each category was calculated as a per cent. The same procedure was used for the comparison of Danish and Norwegian swimming facilities. The average of these two percentages is the estimated savings potential. The findings were then extrapolated to all Norwegian swimming facilities according to their distribution in the three categories, resulting in a total savings potential of approximately 249 GWh per year (Table 4.1).

4.2 Energy performance indicators

One problem that Paper II aimed to solve was the question of whether different EPIs produce different results when applied to the same swimming facilities (RQ3).

Figure 4.8 shows a comparison of the most commonly used EPIs (kWh/m^2_{UA} and kWh/m^2_{WS}) in the literature. The figure shows a widely scattered distribution of data where some of the facilities showing low values when kWh/m^2_{UA} is used, exhibit high values when kWh/m^2_{WS} is applied and vice versa. Furthermore, Spearman's rank correlation coefficient showed a low ($\rho = 0.329$) and highly significant ($p \leq 0.01$) correlation between these two EPIs.

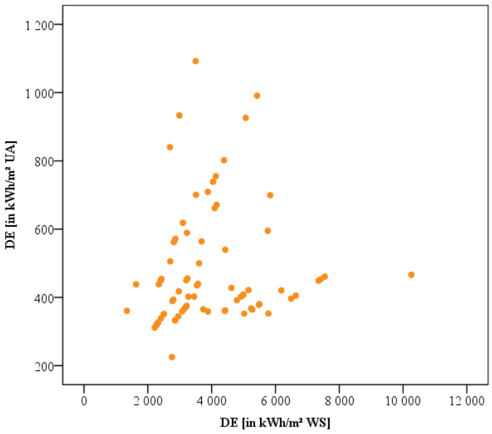

Figure 4.8: *Representation of two EPIs: DE normalised by UA and DE normalized WS.*

To describe the variables included in the correlation and multiple linear regression analyses boxplots are presented in Figure 4.9. The bold line in the middle shows the median where the bottom of the green box represents the 1st quartile and the line on top the 3rd quartile. The whiskers show the minimum and maximum values and the circles and stars represent values SPSS marked as outliers.

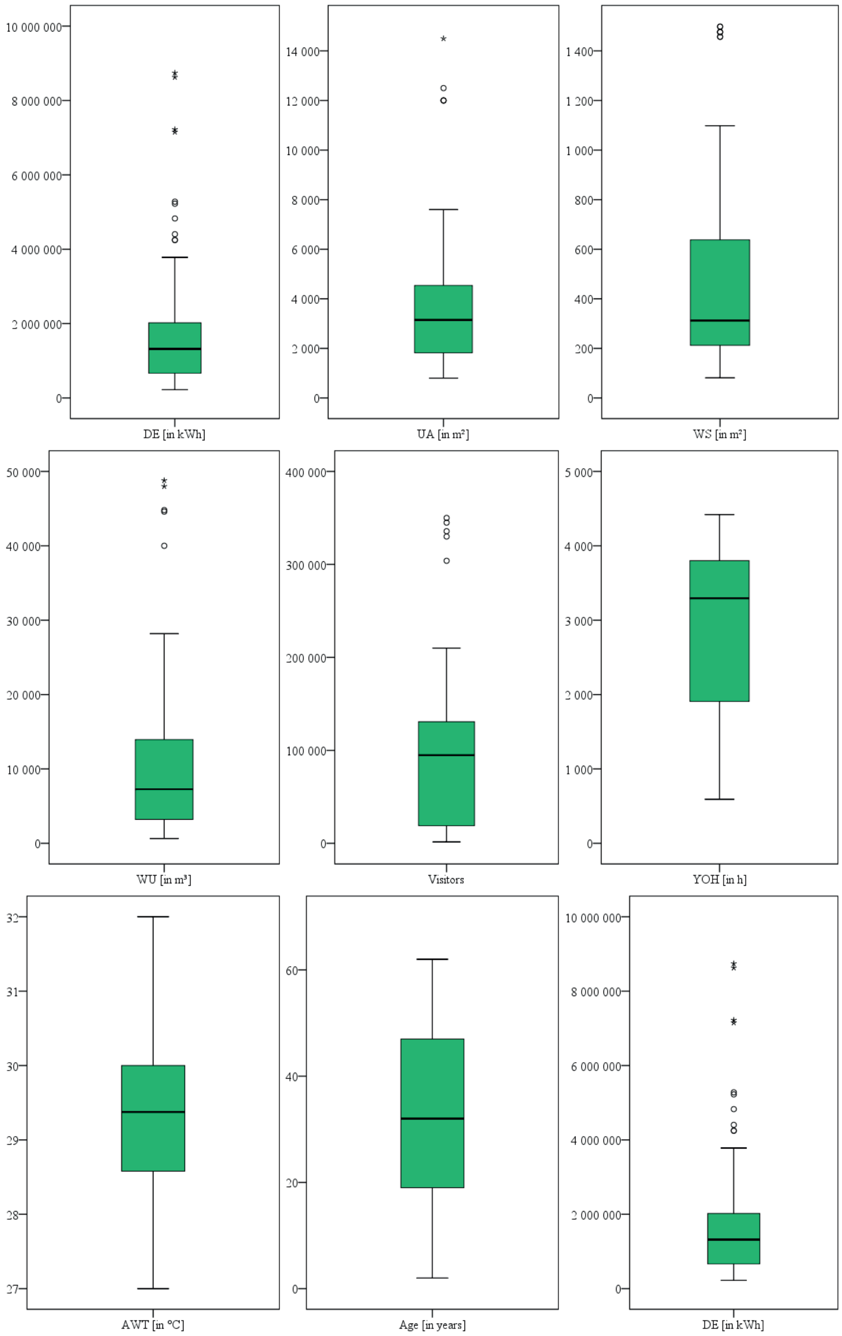

Figure 4.9: *Boxplots of the investigated variables.*

Table 4.2: *Spearman's rank coefficient calculated for each couple of variables stored in the database.*

	DD	Age	UA	WS	WU	AWT	YOH	Visitors
DE	-.280**	-.377**	.866**	.862**	.945**	.059	.595**	.894**
N	176	176	77	176	95	114	105	113
Visitors	-.294**	-.423**	.699**	.906**	.860**	.079	.643**	
N	113	113	41	113	76	100	68	
YOH	.124	-.822**	.550**	.838**	.481**	.116		
N	105	105	63	105	54	70		
AWT	-.146	-.122	-.829**	-.076	.129			
N	114	114	38	114	84			
WU	-.181	-.562**	.888**	.840**				
N	95	95	21	95				
WS	-.239**	-.578**	.827**					
N	176	176	77					
UA	-.454**	-.400**						
N	77	77						
Age	-.064							
N	176							

* significant at the 0.05 level

** significant at the 0.01 level

The correlation analysis (Table 4.2) shows that the correlation between DE and WU is highest, followed by Visitors, UA and WS. DE shows an equally high dependency of UA and WS. On the other side, DE is weakly correlated with climate (HDD_{17}) although statistically significant. The relationship between DE and AWT does not achieve a statistical significant level ($p = 0.05$).

The result of the regression analysis is presented in Table 4.3 where Visitors has clearly the strongest influence on DE followed by age, HDD_{17} and AWT. The results can be expressed through the following regression equation:

$$DE\ (kWh) = 14\left(\frac{kWh}{visitor}\right) * Visitors + 176\left(\frac{kW}{°C}\right) * HDD_{17} - 9\,707\left(\frac{kWh}{year}\right) * Age + 51\,518\left(\frac{kWh}{°C}\right) * AWT - 1\,493\,586\ (kWh)$$

Table 4.3: *Output from the regression analysis.*

	Unstandardized coefficients B	Standard Error	Standardized Coefficients	t	Sig.
Constant	-1 493 586	1 880 057		-0.794	0.430
Visitors	14	1.1	0.847	12.492	0.000
HDD_{17}	176	94	0.113	1.874	0.066
Age	-9 707	4 620	-0.137	-2.101	0.040
AWT	51 518	59 021	0.050	0.873	0.386

The outcome of the model validation is shown in the scatterplot in Figure 4.10 where the modelled DE values are on the x-axis and the measured DE values on the y-axis. Spearman's rank correlation coefficient was calculated resulting in a highly significant (p = 0.000) strong correlation coefficient (p = 0.905).

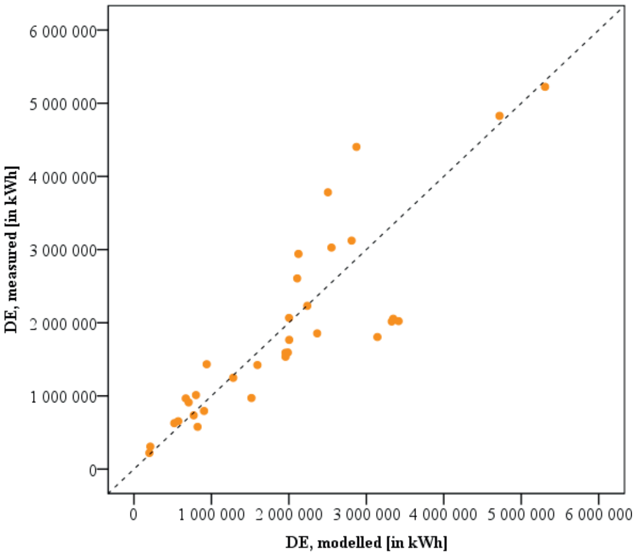

Figure 4.10: *Scatter plot with the comparison of measured and modelled DE.*

The residuals of the validation appear to behave randomly (Figure 4.11, a) and to be normally distributed (Figure 4.11, b); therefore, the developed model seems to fit the data quite well.

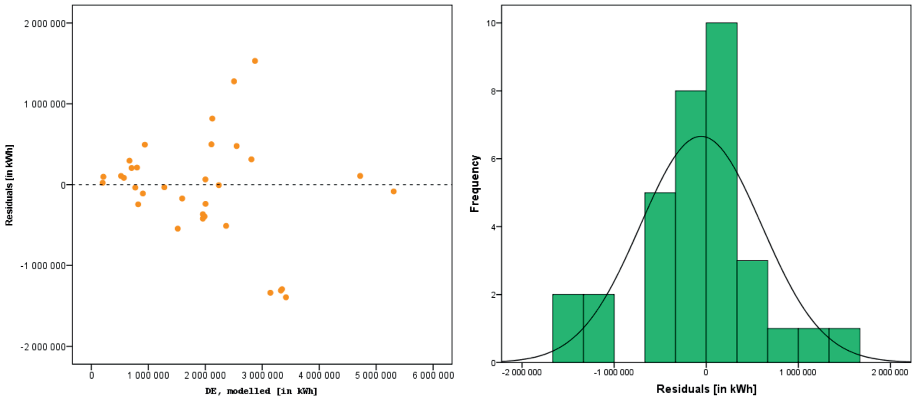

Figure 4.11: *(a) Scatter plot with the comparison of residuals and modelled DE. (b) Histogram of the residuals (normality).*

To measure the accuracy of the model residual statistics were applied yielding in a MAPE of 24.7 %, a MAE of approximately 450 MWh and a RMSE of approximately 660 MWh.

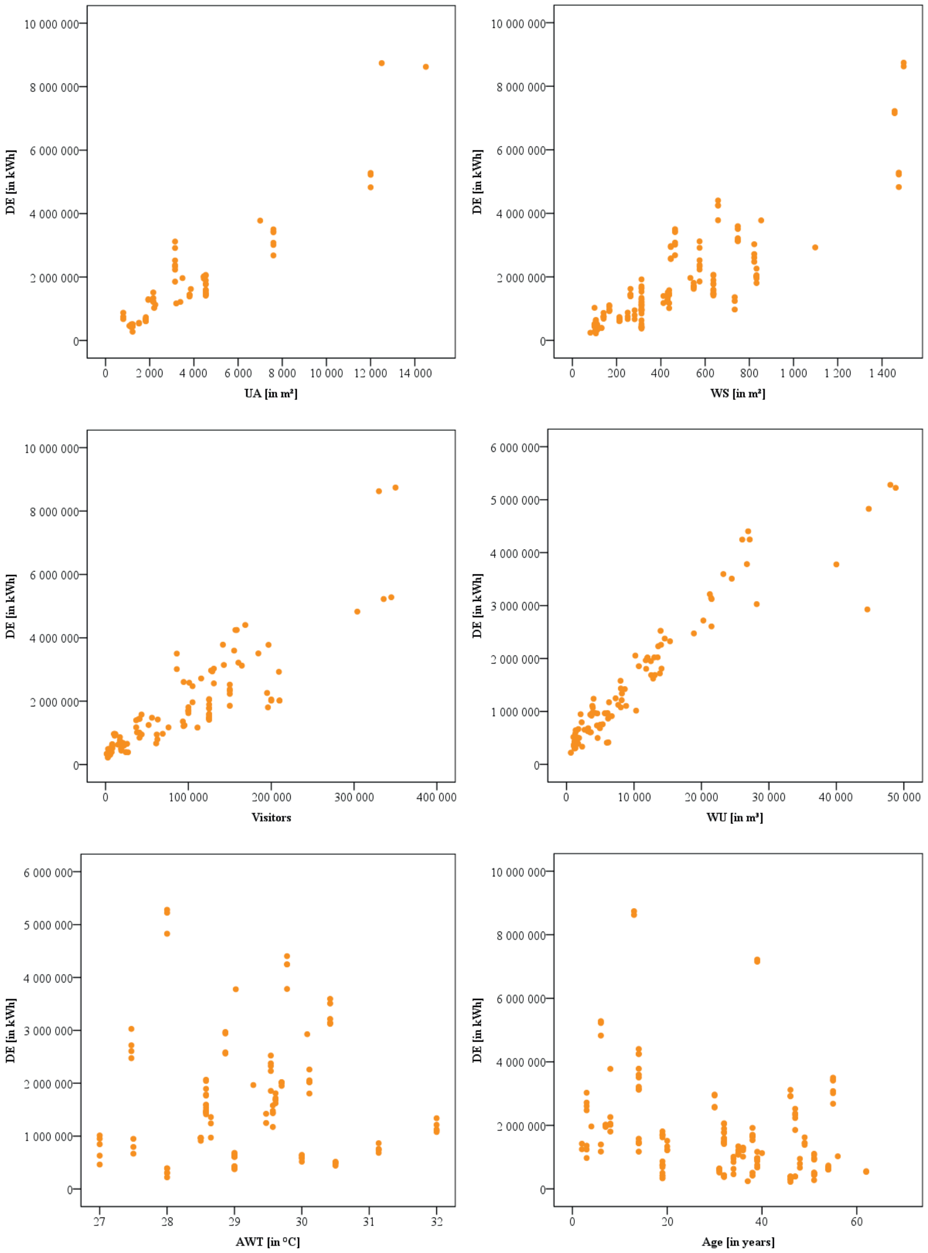

Figure 4.12: *Scatter plots for the DE and the variables of interest.*

To provide a better overview of the spread of the data the scatter plots in Figure 4.12 show DE and the variables of interest.

4.3 Characteristics of energy-efficient swimming facilities

The following chapter deals with the analysis of the 2nd questionnaire that was sent to selected swimming facilities with low energy use.

The water quality requirements are fulfilled by all facilities. Chlorine is used for disinfection, and all facilities use pressurised sand filters. In addition, activated carbon filters in partial flow and UV equipment are used in some facilities. Facilities 1, 2 and 4 are closed during the summer (school holidays), whereas the other facilities are open throughout the year. The collected variables and identified technology for the investigated facilities are shown in Table 4.4.

Table 4.4: *Overview of the collected data for the investigated swimming facilities.*

	Category 1		**Category 2**		**Category 3**	
	Facility 1	**Facility 2**	**Facility 3**	**Facility 4**	**Facility 5**	**Facility 6**
Building year	1966	1969	1995	1982	2008	2007
Annual operating hours	1 404	2 904	3 682	3 294	4 328	4 114
Annual visitors	55 000	44 700	100 000	130 000	365 000	210 000
Air temperature [°C]	30	32	28	30 - 33	31	31
Water temperature [°C]	27.5	28 - 32	28.5	29.6	28	28.9
Humidity [%]	55	55	55	55	55 - 60	60
WS [m^2]	281	312.5	548.5	637.5	1 467	1 170
Water consumption [m^3]	3 563	6 500	13 278	11 817	48 418	16 250
Water consumption per person [l/pers]	65	145	133	91	133	77
FAEC [kWh/m^2 WS/hour opened]	2.93	1.40	0.86	0.78	0.89	0.47
FAEC [kWh/m^2 WS]	4115	4074	3151	2553	3865	1949
Automatic water quality control	✓	✓	✓	✓	✓	✓
Water quality within regulations	✓	✓	✓	✓	✓	✓
Heat pump for filter cleansing (pool refill)				✓		✓
Heat exchanger for grey water (showers)	✓		✓			
Heat pump for grey water (showers)				✓	✓	✓
Heat exchanger in HVAC	✓					
Heat pump in HVAC		✓	✓	✓	✓	✓
Energy from HVAC distributed to air	✓	✓	✓	✓	✓	✓
Energy from HVAC distributed to pool water		✓	✓	✓	✓	✓
Energy from HVAC distributed to tap water		✓		✓		✓

Different concepts were identified concerning filter cleaning. The cleaning procedure varies from all filters being backwashed manually during operating hours to automatic backwash of one filter every day during night time.

The facilities in category 1 are the oldest (older than 40 years). Facility 2 went through a major refurbishment when the HVAC and water treatment system were renewed in 2003. In addition, renovation of the poolroom and an improvement in the envelope insulation were carried out in 2009. Facilities 4 and 6 went through minor renovation of the building envelope (civil works). Facilities 3 and 5 have had no refurbishment or renovations since they were built.

The categories differ significantly in terms of their offered water attractions (Table 4.5). Facilities 1 and 2 have only one small attraction each, whereas facilities 4, 5 and 6 provide a variety of features.

Table 4.5: *Water attractions in different facilities.*

Category 1		Category 2		Category 3	
Facility 1	**Facility 2**	**Facility 3**	**Facility 4**	**Facility 5**	**Facility 6**
small children's slide				small children slide	
	springboard (1 m)				
		slide (55m)	slide (42m)	2 slides (63 m & 67 m)	2 slides (60 m)
		diving plattform	diving plattform	diving plattform	diving plattform
			whirlpool	whirlpool	whirlpool
			sprays	sprays	sprays
			flow channel	flow channel	flow channel
			steam bath	steam bath	steam bath
		sauna	sauna	sauna	sauna
		solarium	solarium	solarium	solarium
					counter current system

Table 4.4 shows the relationship between the technology used for water and energy management and DE. The facilities that use the most advanced systems for energy recovery have the lowest DE. The table illustrates the strong impact of the selection and configuration of technology on annual water and energy use. The described technologies are mainly products from European suppliers and are frequently used in Norwegian swimming facilities.

The energy flux in a plant using the most advanced concepts for energy recovery (facilities 4 and 6) is shown in the flow chart in Figure 4.13. The figure shows only the energy flux inside the building. Two main circuits are illustrated: a short loop for the pool water and a longer loop for the poolroom ventilation. Pool water, tap water and air are all energy carriers.

The embedded heat pump in the air-handling unit recovers energy from the exhaust air from the poolroom and delivers energy for preheating the incoming air, pool water and tap water. The grey water heat pump collects energy from grey water from showers and filter cleansing. Energy recovered by the heat pump is diverted to the tap water, used to refill pools, or further heated for use in showers.

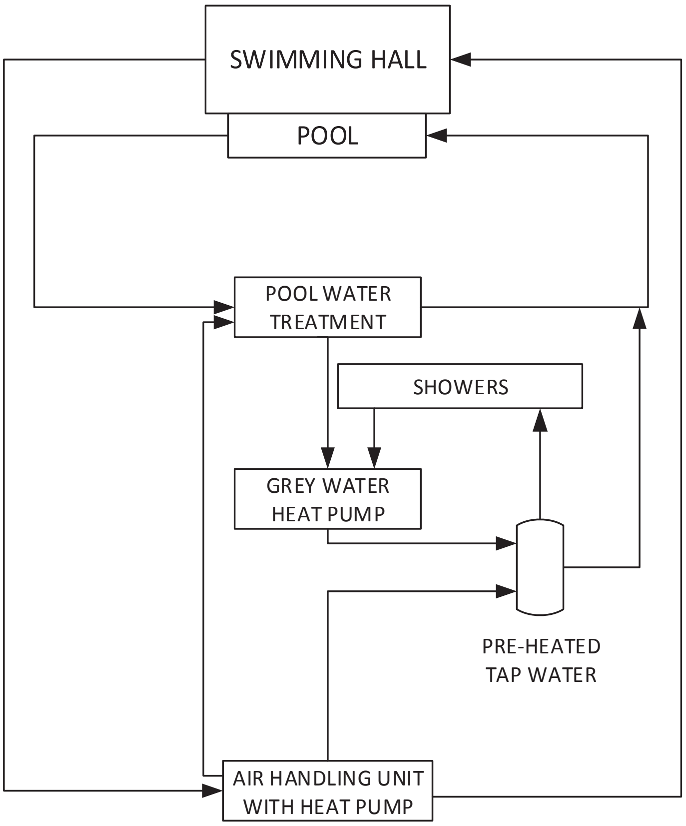

Figure 4.13: *Energy flux for the swimming facilities with the most advanced technology (facilities 4 & 6).*

5 Discussion

5.1 Methodological considerations

When data are collected from field surveys, a detailed discussion is required. The author encountered different challenges, as described below.

5.1.1 Data collection

Data collection was a major challenge, as obtaining accurate and trustworthy information was difficult. Because the owners or maintenance personnel were often not able to see personal gain, the willingness to cooperate was limited in many cases. It was often simple to obtain data from commercially operated leisure pool facilities, whereas municipal swimming facilities were more difficult. After several talks with operational staff, the main problem appeared to be a lack of motivation. The effort and particularly the achieved success in energy savings are rarely rewarded and, in most cases, not even communicated. With a missing feedback system, limited willingness for additional effort is understandable. In this context, municipal swimming facilities are often limited in terms of staff. One employee is often the cashier, maintenance personnel, pool attendant and instructor, occasionally all within one shift. Without receiving any information on their work, the low interest in doing more than expected is not surprising.

Another serious challenge was the lack of water and energy meters in the facilities. Many of the facilities in categories 1 and 2 are combined facilities with sports halls, schools or culture centres also included in the building. In many cases, there was no separate metering of water or energy use for the different units.

The accuracy of the collected data is dependent on the people who reported it. Quality control was applied in the form of checking all reported values and investigating implausible or extreme values closely. If the values in question could not be verified they were excluded from the analyses.

For many of the included facilities, counting visitors accurately is highly demanding. User groups, such as school classes, enter the swimming hall without being counted, distorting the visitor count.

5.1.2 Statistics

The statistics for Paper I include average values, which were taken over the last three years when available. This procedure was chosen to give each swimming facility the same weight in the statistics. Swimming facilities that reported only one year include some uncertainty, as it is unknown whether the DE for the year was high, low or average for the facility.

Because of the non-normal distributed variables, Spearman's correlation coefficient had to be used. This method assigns ranks to the reported values and sorts them accordingly. The ranks are then used to calculate the correlation coefficients, adding some inaccuracy. To provide a deeper understanding of the spread, scatter plots showing the spread are included (Figure 4.12).

5.1.3 Climate correction

Climate correction was applied to all datasets used for the analyses described in chapters 4.1 and 4.3. The method itself is acknowledged [55] and used by several EU member countries [61]. The uncertainty lies within the percentage of the DE affected by climate. This percentage varies by building category, but it can also differ within buildings of one category. According to a guideline for different building types published by ENOVA [56], 40 % of DE in swimming facilities is affected by climate and must be corrected.

A sensitivity analysis was conducted to investigate the impact on the results. Varying the correction percentage with 20 percentage points results in a changed DE of ± 3.04 % with a standard deviation of ± 1.76 %. The correlations in Table 4.2 do not change significantly, with an average deviation of the correlations of ± 0.95 % (std. dev. ± 4.04 %). Both values are strongly influenced by one outlier. Excluding this value from the analysis results in a change in DE of ± 2.85 % (std. dev. ± 1.52 %). The correlations change with ± 0.32 % (std. dev. ± 0.63 %).

5.1.4 Choice of input data

The chosen input data for this thesis were DE as defined in the European standard [47]. The presented work addresses the processes within the swimming facilities. Thus, the thesis focuses on energy use, whereas energy procurement is subject to availability and price structure in each market.

5.1.5 Categorisation

Another source of error could be introduced by dividing all of the swimming facilities into only three groups based on their WS. The dataset shows a considerable variation in YOH, WU, technology, age and annual visitors. The applied categorisation from Paper I was later changed during the thesis work to improve the significance of the developed benchmarks. Creating more categories is preferable but raises the question about which parameter(s) to use for the classification. WS is appropriate, but the borders are extremely strict. This could lead to facilities that are slightly above or below the threshold values to be assigned to the wrong category. To avoid erroneous categorisation, all borderline facilities can be checked manually and assigned to the correct category. This approach was chosen for the analysis of the data presented in Paper III.

5.1.6 Applicability

The results of the energy use of swimming facilities are bound to their respective countries. When transferring them to other regions or countries, the local energy supply and its price structure must be considered. In general, the collected data from the Scandinavian countries appear homogenous, but Denmark exhibits clearly different values. In contrast, Germany, which is farther south, exhibits values that are surprisingly in the range of the Scandinavian countries. Energy use in swimming facilities is dependent on not only the climate and location but also diverse approaches to saving energy, different technologies and variations in building standards. The different national standards concern only the building envelope, not technology. To the knowledge of the author, there are no national guidelines for swimming facilities concerning energy use or WU in general.

The benchmarking approach chosen is applicable worldwide. Differences will occur due to variations in the energy sources available and building standards. Therefore, the EPIs must be used and interpreted accordingly.

The most effective technologies identified are expected to be relevant in similar climates with the same price structure of thermal and electric energy.

5.2 Energy use

Figure 4.1 and Figure 4.2 illustrate the answer for RQ1; Figure 4.1 shows a large variation in DE within the different swimming facilities. This finding is not surprising, as the literature research showed significantly varying values. The unexpected result is the wide spread. The facility with the highest DE uses eleven times the amount of the facility with the lowest DE. The spread can partially be explained by the different purposes that the facilities fulfil.

The different purposes were addressed in Figure 4.2 by dividing all facilities into 3 categories. One aspect influencing the result might be the age of the different facilities. The facilities in category 1 are the oldest buildings on average, whereas the average age in category 2 is 5 years lower. Category 3 includes the newest swimming facilities, with an average age that is one third lower than that of category 2. The newest facilities likely use the most modern technology and maintenance routines and should therefore use less energy. This theory was only partially confirmed by the study. Many of the newest swimming facilities are leisure pool facilities, whose large variety of additional attractions, such as artificial waves, flow channels, saunas, steam baths and large glass facades, actually increase energy use.

The large standard deviation in all of the categories is notable, indicating that swimming facilities with low energy use do exist. In contrast, it also means that some swimming facilities use large amounts of energy. This spread is an indication of the large savings potential for the high-energy-use facilities to be modified to match the energy-efficient facilities. The trend of reduced DE through the decades shown in Figure 4.4 is to be expected. Lower DE can be expected as building codes, technology and operation skills improve. The varying results from the 1960s to the 1990s are most likely random and result from different building sizes, different technologies and different codes of practice.

Swimming facilities built after 2000 were expected to have low DE, but many of these facilities are leisure pool facilities. Therefore, the same arguments presented earlier regarding expectations and findings concerning category 3 are applicable.

To answer RQ2 and analyse possible energy savings, the large variation in the standard deviation was considered. Redesigning and modifying the facilities with high DE should convert them toward the energy-efficient facilities. The average for the best third and the better half of each category are shown in Figure 4.5, along with the per cent value compared with the Norwegian average (Table 4.1). The average of the best third is significantly lower than the average of the total DE. Converting all facilities to this low level of energy use is likely impossible due to the costliness of substantial changes to the building envelope and technologies for aging facilities. Only a slight difference was found when easing the criteria slightly and using average DE of the better half instead of the best third. As a future target, this may be more realistic while still representing considerable potential for saving energy.

Splitting the data into thirds (Figure 4.6) reveals what could be expected when looking at Figure 4.1. Some facilities use a considerable amount of energy, whereas some facilities have extremely low DE. Converting the facilities using the most energy toward the middle third would realise a significant portion of the identified savings potential. The difference between the averages of the middle and best thirds is rather small; therefore, trying to lower the DE of the bottom third to the level of the middle third seems reasonable.

The second possibility for assessing the savings potential and answering RQ2 is comparison with the Danish statistics. These data originated from the Danish Technological Institute website [12], where they are publicly accessible. Figure 4.7 shows the Norwegian and Danish values, compared using the three categories. All values are corrected to match the 2010 Oslo climate to facilitate the comparison.

The Danish datasets are an important estimate of how realistic the analysis is based on Norwegian data.

- The Danish facilities in category 1 use 18 % less energy per year than the Norwegian facilities on average. Expecting a DE reduction of 31 % (compared with the best half) or 32 % (the best third) could be overly optimistic, but the potential improvement is still a significant 25 % (mean of the average of the Norwegian better half and the Danish total average).
- The DE of the Danish swimming facilities is 21 % lower than that of the Norwegian facilities in category 2. Again, the estimations of 37 % and 42 % improvement (compared with the best half and the best third) appear overly high. Taking the average DE from the Danish and Norwegian facilities results in an average improvement of 29 %.
- The largest Danish facilities continue the trend, using approximately half the energy (47 %) of the Norwegian facilities. In this case, the estimate of saving approximately 36 % appears realistic.
- The average energy used by the best third of the Norwegian facilities still uses 564 kWh/m^2_{WS} per year more than the Danish facilities.
- In general, the buildings in category 1 have the largest potential, as they comprise the largest share of all Norwegian facilities (approximately 550 of the 850 facilities), followed by category 2 (280 of 850). Category 3 has the highest saving potential but only accounts for approximately 20 facilities in Norway.
- The annual savings potential for all Norwegian swimming facilities was calculated to be 249 GWh (Table 4.1), which equals approximately 249 million NOK.

Why the Danish facilities perform better than the Norwegian ones was not investigated by the author because the necessary detailed data were not available.

5.3 Energy performance indicators

Figure 4.8 shows a widely scattered distribution of data confirming Øen’s finding [30] that the choice of EPI influences the benchmark of swimming facilities. The choice of EPI is essential (RQ3). However, this does not answer the question of which EPI is better suited to represent energy use in swimming facilities (RQ4). The following paragraphs discuss the different variables, their influence on DE and their applicability for an EPI.

From a statistical point of view UA and WS are equally well suited to be used as normalisation metric in the EPI (Table 4.2). However, the authors suggest to use WS as there is uncertainty bound to UA. Some facilities include the technical areas and some do not which will lead to a skewed analysis. Multi-purpose sports facilities (e.g., a combined swimming pool and sports hall) represent another challenge, as certain areas, such as changing rooms, the entrance area, showers etc., are shared and can lead to a biased analysis. Another interesting observation is that DE is weakly correlated with HDD_{17}, meaning that the climate plays a minor role. Also AWT, which is often suspected to trigger high energy use shows a non-significant very low correlation to DE.

WU and visitors showed a higher correlation with DE and seem to be more appropriate to be used in the EPI. To investigate which of the variables influences DE the most a linear multiple regression analysis was conducted.

To fulfil the assumption of lack of multicollinearity only one variable out of UA, WS, YOH, WU and Visitors could be used in the model. This issue was expected as these variables are interconnected with each other. UA and WS are indicators for the size of the building and are correlated with each other (Table 4.2). The higher these physical parameters, the more visitors the facility will host. WS shows a higher correlation coefficient than UA to Visitors (Table 4.2), which can be explained with the uncertainty connected to UA.

The relation between Visitors, UA and WS is also influenced by YOH (Table 4.2). UA or WS combined with YOH is a natural limitation for total amount of visitors served. A combination of UA or WS with YOH was considered to be the variable used for the regression analysis, but Visitors and WU seem to be more appropriate because of their higher correlations to DE (Table 4.2).

When deciding which of these two variables to include, the uncertainty connected to WU was taken into account. For most of the small and medium sized facilities it is difficult to obtain accurate measurements because they are often part of multi-purpose facilities and do not possess separate meters. Despite that, WU is highly dependent on the number of visitors as they trigger most of the water used in the facility. According to the authors' experience, bleed water and water for showers represents roughly equal water volumes. In theory, both water for showers and bleed water are highly dependent on the visitors. The bleed water need is based on the numbers of visitors but in most cases it is a fixed value based on an approximation of daily visitors. That explains also why WU shows a higher correlation coefficient to DE than Visitors (Table 4.2). Anyhow, because of the number of visitors being the main trigger for WU and DE and the uncertainty connected to WU, the authors included Visitors in the regression analysis.

The result (Table 4.3) shows that Visitors is clearly the variable influencing DE the most. HDD_{17}, representing the climate and AWT have a minor and non-significant influence. The effect of the facilities' age is interesting: the lower the buildings' age the higher DE. A possible explanation is that most of the newer facilities are leisure pool facilities offering a wide range of services to their visitors, leading to increased DE.

The multiple linear regression model provides a reasonably good explanation of how much variance of the energy performance of Norwegian swimming facilities can be explained on the base of the used independent variables. Despite that, the validation shows that the developed model estimates the energy performance of Norwegian swimming facilities with a quite good predictive accuracy on the base of the independent variable, even if the prediction aspect is outside the scope of this thesis.

According to the result of the multiple linear regression analysis and its validation kWh/visitor should be used as EPI. This finding is also in agreement with the approach discussed in the literature [38, 39] where the building is described as a process plant and the process output data (visitors) is used in the EPI.

Leisure pool facilities certainly have accurate numbers for their visitors, but most of the Norwegian swimming facilities are small school pools and multi-purpose facilities [9] that can experience difficulties providing an accurate visitor count, adding uncertainty to the EPI. In this case, kWh/m^2_{WS} should be used as it is an explicit metric that is easy to obtain. When using WS as normalisation metric only buildings providing approximately the same services should be compared.

In addition, the correct interpretation of the EPI is important because it enables a comparison with other buildings. Underlying influencing factors are the building design and equipment, the available energy sources and O&M [36].

5.4 Energy-efficient swimming facilities

RQ5 is answered in chapter 4.3; RQ6 is discussed below.

Even the most energy-efficient swimming facilities in Norway differ significantly in terms of their performance data. The water quality requirements are fulfilled by all facilities. Chlorine is used for disinfection, and all facilities use pressurised sand filters. In addition, activated carbon filter in partial flow and UV equipment for disinfection are used in some facilities. Facilities 1, 2 and 4 are closed during the summer (school holidays), whereas the other facilities are open throughout the year. The collected variables and identified technology for the investigated facilities are shown in Table 4.4.

The two facilities in category 1 differ significantly. Both facilities were built in similar years, but facility 1 did not have any refurbishments. In addition, the HVAC system in facility 2 is more advanced and also recovers energy from wastewater. The WU of facilities 1 and 2 exhibits a major difference, particularly in proportion to the number of visitors. Part of the difference in WU can be explained by the shower flow rates; facility 1 uses 9.75 litres per minute (l/min), whereas facility 2 uses 15 l/min. Facility 2 also exchanges an additional 4 m^3 water daily to maintain water quality.

The difference in energy use between the two facilities in category 2 is approximately 10 %. Facility 4 recovers energy from grey water with more advanced technology, and its HVAC system recovers excess energy for preheating tap water. Facility 4 uses significantly less water per person than facility 3. Part of this difference can be explained by the showerheads (10 l/min instead of 9 l/min).

The two facilities in category 3 exhibit a substantial difference in DE. Facility 5 uses nearly twice as much energy as facility 6. Facility 6 has a more advanced HVAC system, which recovers energy for the tap water and recovers energy from the filter backwash. Facility 5 has a considerably higher WU than facility 6. The flow rate of the showerheads (10 l/min compared to 6 l/min) explains part of the difference. In addition, facility 5 must feed additional bleed water (4.4 m^3/day) to maintain water quality. The horizontal sand filters in facility 5 are less used in Norway; the operator reported that this filter type requires more frequent backwash, increasing WU.

The water used for the showers represents a large share of the total WU. The shower flow rate could affect the visitors' shower use. In addition, different swimming facilities that aim toward different user groups suggest that the visitors' shower usage might differ. Whereas the flow rate is easy to measure, visitor behaviour is less predictable. Some visitors might shower twice or take short showers, whereas others take extensive showers. Based on experience, an average value for the shower duration is 7 min [62].

Facilities 2 and 5 use horizontal sand filters, which are designed with lower surface loads and require more frequent backwashing. Both of the plants using this filter configuration reported a need for an additional feeding of tap water to the pools to achieve satisfactory water quality.

The technology used for energy and water management mainly determines the total usage, whereas the building envelope plays a lesser role [28]. DE is highly correlated to WU (Table 4.2), which is confirmed by the facilities in categories 2 and 3. Therefore, an energy analysis must always include a water balance analysis. The influence of the WU on the energy use is highly dependent on the used technology.

Low WU does not necessarily result in a low DE, but the two facilities with the lowest DE used small amounts of water. Part of the significant difference in WU can be explained by the showerhead flow rates and the use of bleed water to maintain water quality within regulations. However, these two factors do not account for all of the differences found, leaving some of the factors unexplained.

Facilities that redirect recovered energy from the ventilation system to pool and tap water were found to have a lower DE. As stated in the literature, swimming facilities have a substantial surplus of energy in the exhaust air from the pool room, especially in the summer months [28, 41]. In a published case study from Shanghai [41], the recovered energy from the HVAC system was sufficient to heat the pool water for more than eight months each year. By not recovering this energy, facility 1 has significant energy savings potential. A smaller savings potential was detected in facilities 3 and 5, as they do not recover energy from exhaust air to tap water.

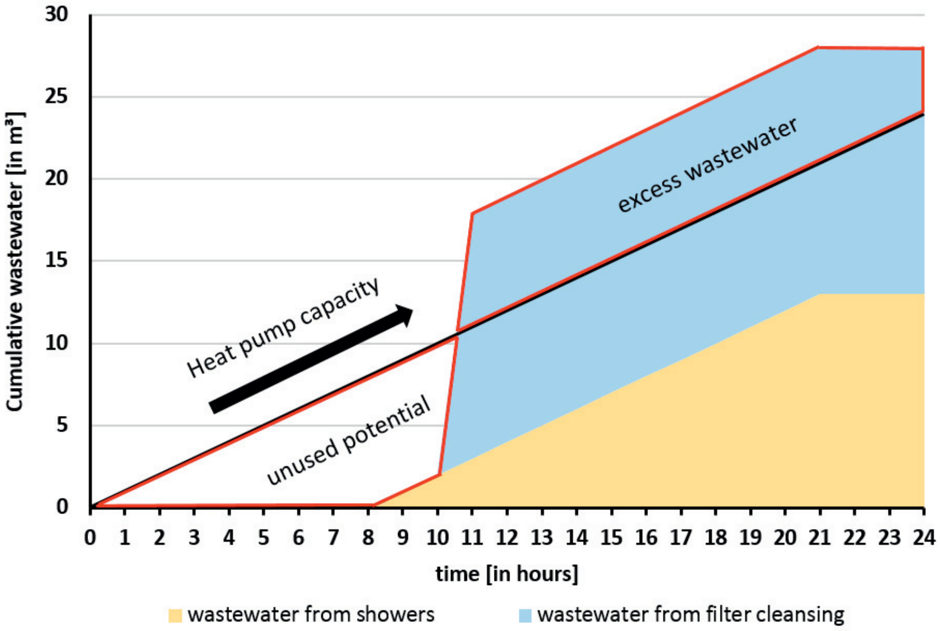

Figure 5.1: *Illustration of typical wastewater management in the investigated facilities.*

Figure 5.1 shows the backwash of filters during the operating hours, which is the standard procedure in most facilities but is not recommended. Filter cleansing during operating hours results in a peak water and energy demand, raising the capacity demand for the heat pump beyond economical limits. Large holding tanks could be used to collect all of the wastewater, but a larger holding tank has a higher initial cost. Additionally, the space filled by such a tank might pose a challenge for the facility. Therefore, the pool should be refilled slowly during the night to guarantee optimal utilisation of the heat pump.

The technology is not new, and many aspects are described in the literature. Chan & Lam [63] described water-water heat recovery in swimming facilities. Energy recovery from air to air has been known since the 1960s and has been improved over the past few decades. Two articles [41, 64] describe an HVAC system recovering energy from exhaust air to preheat incoming air and pool water. The most advanced solutions identified in this study exhibit a slightly more sophisticated system in which the recovered energy is used to heat the incoming air, pool water and tap water (Figure 4.13). After the condensers, an after cooler for preheating the tap water can recover the remaining energy. The condensers for the air and pool water must be arranged in parallel. When arranged in series, the heat pump will stop when the air reaches the desired temperature and stop delivering energy to pool and tap water. This is usually the case as the enthalpy of the exhaust air is higher than the enthalpy of the supply air because of evaporation. The solution found in most of the investigated swimming facilities had the possibility to bypass the condenser for the supply air and is illustrated in Figure 5.2.

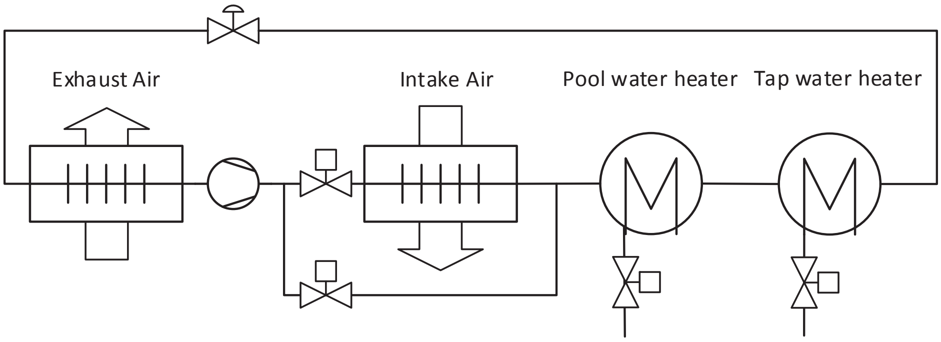

Figure 5.2: *Illustration of the heat recovery in the HVAC system.*

The effect of water attractions on the energy use has not been thoroughly investigated. However, energy use is increased due to the heat loss of the additional evaporation, but most of the energy can be recovered with modern technology. Another contributor to energy use is the electricity needed to operate the pumps, which is dependent on the usage pattern of each attraction.

Additionally, appropriate O&M of a swimming facility is essential. Similar to other process plants, skilled O&M is mandatory to achieve the desired output parameters and keep costs down. The lack of control systems to detect and indicate deviation and malfunction in a way operators are able to understand was observed in several cases. A promising approach is to develop a tailor-made interaction design which takes the skills of the O&M personnel into account. Another important step is to merge the various interfaces from the different technology suppliers into one.

The author chose not to present the potential of the identified most profitable measures. Estimating the cost and therewith payback time is dependent on several different factors and would not reflect a generally valid solutions.

5.5 Future swimming facility projects

The objective of this thesis is to describe energy use in pool facilities, including a better understanding of those that are performing well. A reasonable outcome of the work is to describe the desirable characteristics of new swimming facilities, aiming for the best possible energy and water balance. Local price structures for electricity and thermal energy will have a strong impact on the design concepts and must be assessed in the initial design stage.

The study found that good facilities exist, but even the better facilities showed unused potential that could be realised. Furthermore, although advanced technology is available on the market, applications are limited to the existing knowledge about design, configuration and operation.

5.5.1 Building envelope

Europe converges toward the passive house standard for building standards. Passive house concepts mainly consider the building envelope and are being increasingly introduced to sports facilities. For swimming facilities, neither a standard nor a best practice code exists for the energy use of the overall facility. Thus, stating that a sports facility is fulfilling the most advanced building code with respect to energy use is only a partial truth. The major part of the energy use is related to the operation of the process systems in the facility.

The following may be a guideline for the design work:

- U-values may be selected as per the preferred code. Windows should be designed in accordance with best available technology.
- The building envelope must be well sealed to avoid infiltration losses and vapour transport.
- Pressure differences between the poolroom and ambient rooms and across the building envelope must be controlled by the HVAC system and kept as low as possible.

5.5.2 HVAC system

In the North European context, the use of advanced HVAC systems with static heat exchangers and heat pumps for energy recovery is well established. These units combine airflow and pressure control of the room with humidity and temperature monitoring and control. An integrated heat pump allows for energy recovery. To utilise the fluctuations in surplus energy recovered by the heat pump, heat transfer must be arranged to preheat air, pool water and tap water. Combining storage tanks for grey water as well as preheated tap water allows for stable tap water flow for showers during operating hours and for refilling pools at night. The collected data showed that accumulation and reuse of condensate from the dehumidification of the HVAC system may represent up to 5 % of the total WU.

5.5.3 Water balance

The water bill for a pool facility is a substantial part of the operational budget, and thus, keeping WU low is an important goal for the designer and operator. Collecting grey water from showers and backwash water from filters, including the energy recovery of this flow, is economically profitable in most facilities. Water-efficient showerheads with a flow of 9–10 l/min are available on the market. In the author’s experience, the total wastewater consists of approximately 50 % wastewater from the showers and 50 % wastewater from the backwash of filters. The latter is usually designed in a way to meet Norwegian guidelines [17] for water exchange.

To capitalise on all of the described energy surpluses [28, 41], a combination of water and energy systems is necessary, including a heat pump and holding tanks for grey water and preheated tap water. One tank is needed to store the excess wastewater and serve as energy storage; the other tank stores the recovered energy in the form of preheated water and uses the otherwise unused potential of the heat pump (Figure 5.1). The WU by the visitors during the day fills the storage tank during the operating hours. Filter backwash outside the operating times provides an energy source for the heat pump. This system allows the heat pump to recover energy from grey water and be operational around the clock, which is illustrated in Figure 5.3.

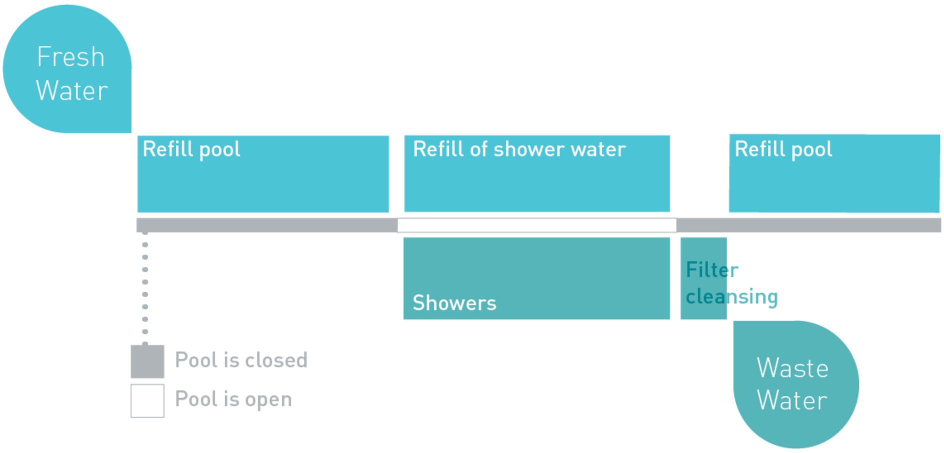

Figure 5.3: *Example of wastewater management.*

The management of wastewater and fresh water is essential to optimise energy recovery from water. Generating wastewater from the filter backwash and showers leads to peak flows, which are difficult to address when designing energy recovery systems. Flushing the filters during the night reduces the peak and allows for smaller storage tanks that are easier to fit into the facility and have a lower cost. This also allows the pool water to be refilled slowly over a long period instead of all at once when done during operating hours.

The heat pump should be operational for as many hours as possible during the day, which is key to a good economy.

5.5.4 Evaporation

The literature shows that evaporation is the single largest energy user in swimming facilities [14, 26-28]. Accordingly, the HVAC system has to operate day and night. Efforts have been made to reduce evaporation with solid and fluid pool covers; these can be a useful measure, but practical use is dependent on local conditions. Pool covers are effective if the swimming facility is closed during long periods of the day (typically small school pools). With a sophisticated system design and an effective HVAC system, which recovers most of the evaporation energy, the outcome concerning energy will almost be the same. In addition, no extra investment is necessary, working hours are saved and the risk of visitors or personnel getting trapped under the pool cover is eliminated. Damage to the building envelope because of moisture is unlikely to occur as the evaporation rate during the closing hours is low. If moveable pool floors are used they should stay above the water surface when the facility is closed, which has the same effect as a pool cover. To the knowledge of the author, no reports are available concerning the long-term use of pool covers in indoor facilities. The use of movable pool floors allows the pool floor to be lifted to above the WS during night hours so that the pool cover is in place without additional investments.

The major contribution to electrical energy savings in the facility is demand-controlled operation of pumps. Reduction of flow in low-load periods may provide a substantial reduction in electricity use if allowed by the hydraulic design.

5.5.5 Control systems

One of the important findings in this thesis is that a pool facility is not a traditional building but rather a process plant. Therefore, an industrial style control and SCADA system should be part of the scope. Integration of the pool water control system, HVAC system, sauna, lighting and other building services in a common control system is recommended. This integration allows for the highest possible energy recovery, which might exceed the designed capacity of the system. Energy and water meters on each subsystem is necessary to monitor use, detect malfunctions and for documentation over time. Monitoring and documentation of water quality, as required by the authorities, may be combined with process control of the same parameters.

A system reporting the operational status of all subsystems and possible deviations to the operators must be included. In particular, issues related to process equipment and health, safety and environment (HSE) may be implemented.

5.5.6 Operation and Maintenance

The requirements for the staff of swimming facilities have changed considerably with the implementation of modern technology. Educated and trained personnel are essential for the operation of a process plant. Limited or no formal education is available in swimming facilities. The operators are normally involved in a combination of different tasks, ranging from pool attendance to ticket sales, water sampling and building and plant maintenance. Except for the larger leisure pool facilities, the ownership and operation are split. In some cases, the operators receive limited or no feedback from the owners on how the use of water and energy is reflected in the O&M budget. Municipalities with small school pools are not able to hire a full-time pool operator. One possible solution could be to hire one skilled operator who is responsible for several plants.

6 Conclusion

6.1 Conclusions

RQ1:

The statistics presented in this work are collected from four different countries: Denmark, Finland, Germany and Norway. The focus was on Norwegian swimming facilities but all collected data shows large variations concerning energy use. The in-depth analysis of the Norwegian and Danish datasets implies a substantial potential for energy savings and therewith lower cost and less environmental impact.

RQ2:

Extrapolating the generated statistics, the DE for all 850 Norwegian swimming facilities is approximately 883 GWh/year. If the assumptions regarding savings potential (Table 4.1) are valid, the annual energy use of all Norwegian swimming facilities can be reduced by approximately 28 %, or 246.5 GWh/year. Specific measures were not investigated.

RQ3:

Significant differences in the rating of swimming facilities' energy use were found when applying different EPIs, meaning that the choice of EPI is important.

RQ4:

If reliable data are available, visitors should be used in the EPI (kWh/visitors) when benchmarking swimming facilities. Obtaining consistent data concerning visitors can be challenging and the author suggests using WS in the EPI (kWh/m$^2_{WS}$) for these cases. Further, when using kWh/m$^2_{WS}$, only buildings offering (approximately) the same services to their visitors should be compared.

RQ5:

Swimming facilities with low energy use were found to use technology and a system design to recover energy from air and water effectively. The recovered energy is then redistributed to air and water. Facilities using the most advanced technology used the least energy. It was also observed that the operating personnel at these facilities received good training and showed high motivation to reduce energy use.

RQ6:

Reverting the finding from RQ5, facilities with high energy use should investigate the possibilities to install energy recovery technology to realise a reduction of their energy use. With Norwegian climate and energy prices, energy recovery is best achieved using heat pumps. The HVAC systems must be designed to recover energy from the air and preheat the incoming air, pool water and tap water.

6.2 Contributions

Statistics in the dimension and extent as presented in this thesis have, to the knowledge of the author, not been previously published in the literature on this topic. Although some publications estimate savings potential on a few facilities, the executed analysis is based on a considerably larger sample size. This reduces uncertainty and is an important first step to understanding the high energy use in this building type.

Energy use in swimming facilities is discussed in the literature to some extent, but very few publications analysing the origin of the high energy use were found in the literature review. The presented correlations show the strength and significance of the dependencies of variables that were suspected to influence energy use. These findings were further used to develop a consistent EPI. These indicators are a fundamental tool to represent energy use in swimming facilities, enabling comparisons between swimming facilities and identification of savings potential.

The investigation of energy-efficient swimming facilities has, to the knowledge of the author, not been conducted on a scientific level. The interaction between used technology at the sites and their energy use has not been published before. A further developed HVAC and water treatment system could be identified and described. Further, this analysis enables the design of future swimming facilities with lower energy use.

6.3 Future work

The findings concerning energy use and the EPIs are based on a dataset with the largest detailed published sample size in this research area. However, data must be collected from more swimming facilities over several years to strengthen the analysis. A sufficiently large sample would allow each of the three categories to be analysed separately, accounting for the different offered services and user groups.

Another task for the future is to acquire data from countries in warmer regions and compare them with the data of the Northern European countries presented in this thesis. The parameters governing energy use will likely differ from those presented in this thesis. Hence, different solutions can be found to achieve energy-efficient buildings in other climates.

Swimming facilities with low energy use have not been previously analysed in detail. The presented work can be seen as a first step, but many aspects are still unknown and have to be investigated. A good place to start would be Danish swimming facilities with their low energy use.

With visitors being the main trigger for energy use variations during and outside operating hours should be investigated. Reducing the different subsystems to a minimum level to save energy while the facility is not in use is the goal.

The impact of air inlet and outlet design in pool rooms is not well developed; further research on the topic should include studies on the room climate for swimmers, operators and spectators. Of particular interest is CO_2 as well as aerosols containing disinfection by-products.

In addition, the U-values of the different elements included in the building envelope has been reduced substantially during the recent three decades. In particular interesting is the resulting reduced heat flux through the windows. The traditional design is based on air inlet below the windows to avoid the humid room air to stay close to the glass and frame, and subsequently cause condensation. With modern window design, the risk of condensation on the glass surface is reduced. Accordingly, the total heat loss through the construction is reduced, which might allow for a new approach concerning ventilation in pool halls.

The distribution of energy use in swimming facilities is discussed in the literature to some extent. Most of the reported numbers are calculated or based on case studies. Measuring and investigating more swimming facilities to identify the subsystems using most energy would also be of interest.

References

[1] International Energy Agency, Key World Energy Statistics, 2013.

[2] Energy Information Administration, International Energy Outlook, 2013.

[3] N. Lior, Sustainable energy development: The present (2009) situation and possible paths to the future, Energy, 35 (10) (2010) 3976-94.

[4] United Nations, World Population to 2300, 2004.

[5] European Union, EUROPA - Topics of the European Union - Energy, http://europa.eu/pol/ener/index_en.htm, (accessed 07.08.2015).

[6] International Energy Agency, Energy efficiency, http://www.iea.org/aboutus/faqs/energyefficiency/, (accessed 07.08.2015).

[7] Statens Energimyndighet, Energianvändning i idrottsanläggningar, 2009.

[8] ENOVA, Energibruk i ulike bygningstyper, http://www.enova.no/innsikt/rapporter/byggstatistikk-2011/4-energibruk-2011/43-energibruk-i-ulike-bygningstyper/43-energibruk-i-ulike-bygningstyper/490/1233/, (accessed 07.08.2015).

[9] Kulturdepartement, Idrettsanleggsregisteret, http://data.norge.no/data/kulturdepartementet/idrettsanleggsregisteret/, (accessed 07.08.2015).

[10] Great Britain: Energy Efficiency Office, Energy use in sports and recreation buildings, 2001.

[11] Deutsche Gesellschaft für das Badewesen e.V., ÜÖBV-Report, Essen, 2012.

[12] Teknologisk Institut, Nøgletal, energi- og vandforbrug i svømmehaller - Nøgletal fra 2006-2011, http://www.teknologisk.dk/ydelser/noegletal-energi-og-vandforbrug-i-svoemmehaller/noegletal-fra-2006-2011/21324, (accessed 07.08.2015).

[13] Opetusministeriö, Uimahalliportalli - Uimahallien energia- ja ympäristöportaali, http://uimahallit.vtt.fi/, (accessed 07.08.2015).

[14] British Swimming, The Use of Energy In Swimming Pools, 2008.

[15] C. Saunus, Schwimmbäder, Planung - Ausführung - Betrieb, Krammer Verlag Düsseldorf AG, Düsseldorf, 2005.

[16] T. Bøhlerengen, J. Mehus, A. Waldum, P. Blom, T. Farstad, Byggforsk håndbok 52: Bade og svømmeanlegg, Norges Byggforskningsinstitutt, Oslo, 2004.

[17] Norsk Bassengbadeteknisk Forening, Retningslinjer for vannbehandlign i offentlige bassengbad, 2000.

[18] P.J. Dennis, D. Green, B.P.C. Jones, A note on the temperature tolerance of Legionella, Journal of Applied Bacteriology, 56 (2) (1984) 349-50.

[19] P.J. Dennis, Legionnaires' disease — preventative maintenance, Journal of the Institute of Hospital Engineering, 42 (1988) 14 - 5.

[20] World Health Organisation, Guidelines for safe recreational-water environments, Volume 2: Swimming pools and similar environments, 2006.

[21] DIN Deutsches Institut für Normung e.V., DIN 1943:2012-11 - Treatment of water of swimming pools and baths, 2012.

[22] Ministry of Health and Care Services, Forskrift for badeanlegg, bassengbad og badstu, in, Ministry of Health and Care Services, Oslo, 1996.

[23] Norsk Institutt for Vannforskning (NIVA), Vannkvalitet og vannbehandling i bade- og svømmeanlegg, 2000.

[24] M.M. Shah, Prediction of evaporation from occupied indoor swimming pools, Energy and Buildings, 35 (7) (2003) 707-13.

[25] M.M. Shah, Improved method for calculating evaporation from indoor water pools, Energy and Buildings, 49 (0) (2012) 306-9.

[26] A. Saari, T. Sekki, Energy Consumption of a Public Swimming Bath, The Open Construction and Building Technology Journal, 2 (0) (2008) 202 - 6.

[27] E. Trianti-Stourna, K. Spyropoulou, C. Theofylaktos, K. Droutsa, C.A. Balaras, M. Santamouris, D.N. Asimakopoulos, G. Lazaropoulou, N. Papanikolaou, Energy conservation strategies for sports centers: Part B. Swimming pools, Energy and Buildings, 27 (2) (1998) 123-35.

[28] H. Røkenes, Betraktninger rundt svømmehallers energieffektivitet [Master thesis], NTNU, 2011.

[29] A.S. Abrahamsen, M. Bergh, N. Fedoryshyn, Statistics Norway - Energibruk i bygninger for tjenesteytende virksomhet 2011, 2013.

[30] M. Øen, Indoor Swimming Pools and Requirements for Energy Efficiency [Master Thesis], Trondheim: Norwegian University of Science and Technology, 2010.

[31] X. Xu, Model-based building performance evaluation and diagnosis [Dissertation], Hong Kong: The Hong Kong Polytechnic University, 2005.

[32] D. Claridge, C. Culp, S. Deng, W. Turner, J. Haberl, M. Liu, Campus-Wide Continuous Commissioning of University Buildings, In: Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA, 2000.

[33] S. Wang, C. Yan, F. Xiao, Quantitative energy performance assessment methods for existing buildings, Energy and Buildings, 55 (0) (2012) 873-88.

[34] Concerted Action EPBD, Concerted action - energy performance of buildings, http://epbd-ca.eu (accessed 07.08.2015).

[35] D. Goldstein, C. Eley, A classification of building energy performance indices, Energy Efficiency, 7 (2) (2014) 353-75.

[36] D. Goldstein, J. Almaguer, Developing a Suite of Energy Performance Indicatiors (EnPIs) to Optimize Outcomes, In: Proceedings of the 2013 ACEEE Summer Study on Energy Efficiency in Industry, Washington, D.C., American Council for an Energy-Efficient Economy, 2013.

[37] ProMidNord, Best practices in spas - Energy efficient and environmentally responsible operation modes in Mid Nordic and European public swimming pools and spas, 2007.

[38] D. Saygin, E. Worrell, M.K. Patel, D.J. Gielen, Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries, Energy, 36 (11) (2011) 6661-73.

[39] L. Pérez-Lombard, J. Ortiz, R. González, I.R. Maestre, A review of benchmarking, rating and labelling concepts within the framework of building energy certification schemes, Energy and Buildings, 41 (3) (2009) 272-8.

[40] European Parliament, Directive on the energy performance of buildings, France: European Parliament, 2002.

[41] P. Sun, J.Y. Wu, R.Z. Wang, Y.X. Xu, Analysis of indoor environmental conditions and heat pump energy supply systems in indoor swimming pools, Energy and Buildings, 43 (5) (2011) 1071-80.

[42] Carbon Trust, Swimming pools: A deeper look at energy efficiency, 2008.

[43] B.F. Blumberg, D.R. Cooper, P.S. Schindler, Business research methods, 4th Edition ed., McGraw-Hill Education, New York, 2014.

[44] R.K. Yin, Case Study Research, Design and Methods, 4th Edition ed., SAGE Inc., Thousand Oaks, 2009.

[45] A. Fink, How to conduct surveys, a step-by-step guide, SAGE Publications, Thousand Oaks, 2013.

[46] Ministry of Culture, Statusrapportering for svømmebasseng - 2012, Oslo: 2013.

[47] EN 15217:2007, Energy performance of buildings—methods for expressing energy performance and for energy certification of buildings, 2007.

[48] EN 15603:2008, Energy performance of buildings. Overall energy use and definition of energy ratings 2008.

[49] International Organization for Standardization, ISO/TR 16344:2012: Energy performance of buildings - Common terms, definitions and symbols for the overall energy performance rating and certification, 2012.

[50] P. Torcellini, S. Pless, M. Deru, D. Crawley, Zero Energy Buildings: A Critical Look at the Definition, in: ACEEE Summer Study, Pacific Grove, California, USA, 2006.

[51] F.J. Harrell, K. Lee, D. Mark, Multivariableprognostic models: issues in developing models, evaluating assumptions and adequacy, and measuring and reducing errors, Statistics in medicine, 15 (1996) 361 - 87.

[52] International Organization for Standardization, ISO 9836:2011: Performance standards in building - definition and calculation of area and space indicators, 2011.

[53] Meteo Norge, Kommentarer til beregning av energi gradtall 2014 (Comments on the calculation of the degree-days of 2014), 2015.

[54] ENOVA, Enovas byggstatistikk 2010, 2010.

[55] Pöyry Management Consulting AS, Evaluering av modeller for klimajustering av energibruk, 2014.

[56] ENOVA, Enovas byggstatistikk 2008, 2008.

[57] Danish Meteorological Institute, DMI - Vejret i Danmark, http://www.dmi.dk, (accessed 07.08.2015).

[58] Finnish Meteorological Institute, Heating degree days - Ilmatieteen laitos, http://en.ilmatieteenlaitos.fi/heating-degree-days, (accessed 07.08.2015).

[59] Deutscher Wetterdienst, Weather and Climate - Deutscher Wetterdienst, http://www.dwd.de/, (accessed 07.08.2015).

[60] ENOVA, Graddagstall, http://www.enova.no/radgivning/naring/praktiske-ressurser/bygningsnettverket/graddagstall/290/0 (accessed 07.08.2015).

[61] European Union, Implementing the Energy Performance of Buildings Directive (EPBD), 2010.

[62] A.M. Thomassen, Utbedring av svømmehall [Master thesis], NTNU, 2013.

[63] W.W. Chan, J.C. Lam, Energy-saving supporting tourism sustainability: A case study of hotel swimming pool heat pump, Journal of Sustainable Tourism, 11 (1) (2003) 74-83.

[64] L. Johansson, L. Westerlund, Energy savings in indoor swimming-pools: comparison between different heat-recovery systems, Applied Energy, 70 (4) (2001) 281-303.

Appendix A: Questionnaire 1

ENERGY USE IN SWIMMING FACILITIES

The Centre for Sport Facilities and Technology (SIAT) at the Norwegian University of Science and Technology (NTNU) works on investigating energy consumption in sports facilities where our main focus is on swimming facilities. The data collection is paired with developing new concepts for water- and energy consumption with the aim of reducing energy consumption and maintenance cost in Norwegian swimming facilities.

We work together with the Ministry of Culture (KUD) allowing us to access its database including all Norwegian sports facilities which gives us the size and building year of most of the public swimming facilities in Norway. The best possible data background is necessary for our work and therefore we ask you about the following information about your swimming facility:

1. **Information about your facility**

Name	
Address	
Postcode	
Place	
Community	

2. **Energy consumption (kWh/year)**

		2006	**2007**	**2008**	**2009**	**2010**
Energy total	**kWh/year**					
Electricity	kWh/year					
Thermal energy	kWh/year					

3. **Water consumption (m^3/year)**

		2006	**2007**	**2008**	**2009**	**2010**
Water consumption	**m^3/year**					

4. **Visitors per year (school + public)**

		2006	**2007**	**2008**	**2009**	**2010**
Visitors	**Persons/year**					

5. **Pools**

   Which type (sports-, therapy pool, whirlpool…) pool exist? Size (length and width)? Water temperature as weekly average for the different pools?

Pools	**Type**	**Length and width**	**Temperature in °C**
Example	*Sports pool*	*25m x 12.5m*	*27 °C*
Pool 1			
Pool 2			
Pool 3			

The collected information will be used to create a national overview over water- and energy consumption in swimming facilities with the goal to develop energy performance indicators or variables to aid the planning process of refurbishments, new buildings or change of maintenance routines.

Thank you in advance for your help. You will receive a general analysis in addition to a personal letter where your swimming facility will be shown explicitly. We can process the date ourselves in case of your data being in raw format.

We would like to receive your answer with the 22. February 2011 to Wolfgang Kampel, wolfgang.kampel@ntnu.no

NTNU – Trondheim
Norwegian University of
Science and Technology

Centre for Sport Facilities and Technology

www.ntnu.no/siat

Appendix B: Questionnaire 2

Checklist swimming hall

Facility name: Click here to enter text.
Contact person (Name and phone): Click here to enter text.

Total annual energy consumption				
2008	**2009**	**2010**	**2011**	**2012**
Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.

Building year: Click here to enter text.
Rehabilitation (when & what): Click here to enter text.
Weekly opening hours Click here to enter text.
Closed periods Click here to enter text.
Number of employees (what kind of employment?) Click here to enter text.

Yearly visitors Click here to enter text.
  School (if available) Click here to enter text.
  Rental (if available) Click here to enter text.
  Paying audience (if available) Click here to enter text.
  Others (if available) Click here to enter text.

Building envelope:
  U-values:
    Walls Click here to enter text.
    Roof Click here to enter text.
    Floor Click here to enter text.
    Window area in % of facade Click here to enter text.

Air temperature Click here to enter text.
Relative humidity: Click here to enter text.
Chlorine or chlorine free? Click here to enter text.

Is water quality within regulations? Yes ☐ No ☐

Is water quality steered automatically? Yes ☐ No ☐

Amount of water circulation (normal operation and maximum): Specify if several circuits exist and which pools are connected to which circuitClick here to enter text.

Heat exchanger for pool water? Yes ☐ No ☐

Heat pump for grey water? Yes ☐ No ☐

Preheating of water before it enters the system? Yes ☐ No ☐

Pools (for example: sports pool, therapy pool, whirlpool, etc)

Pool (sports pool, therapy pool, wave pool, etc)	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.
Size (length, width, depth)	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.
Water temperature	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.

Annual water consumption				
2008	**2009**	**2010**	**2011**	**2012**
Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.

Lighting:

Which bulbs are used? Click here to enter text.

Movement sensors? Where? Click here to enter text.

Attractions

Slide Yes ☐ No ☐

Diving platform Yes ☐ No ☐

Whirlpool Yes ☐ No ☐

Others Click here to enter text.

Filters

Type and amount Click here to enter text.

Capacity Click here to enter text.

Automatic or manual flushing? When? Click here to enter text.

What happens to the water from filter cleansing? Is it directed directly to the sewer or via a heat recovery system? Click here to enter text.

HVAC

Brand/product Click here to enter text.

Airflow per day/week/month Click here to enter text.

Amount of fresh air? As required? Percentage? Click here to enter text.

Heat pump? Yes ☐No ☐ Product? Click here to enter text.

Energy recovered …

to air? Yes ☐ No ☐ Product? Click here to enter text.

to pool water? Yes ☐ No ☐ Product? Click here to enter text.

to water for showers? Yes ☐ No ☐ Product? Click here to enter text.

Comments

Click here to enter text.

In case of uncertainties or if you have questions contact:

Wolfgang Kampel

Tlf: 45134270

wolfgang.kampel@ntnu.no

Appendix C: Papers

Appendix C includes the papers of the authors PhD work. Papers I and III are published while Paper II is under review. The author chose to format the papers in the appendix in the same way as the thesis.

Paper I

Kampel, W., Aas, B. and Bruland, A., Energy-use in Norwegian swimming halls. Energy and Buildings, 59 (2013), p 181 – 186.

DOI: 10.1016/j.enbuild.2012.11.011

Energy use in Norwegian Swimming Halls

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Abstract

Norway has about 850 swimming facilities with an average age of 37 years. A questionnaire issued to facility operators gave, in total, about 100 answers, and the received datasets were analyzed and verified. This article contains data from a selection of 41 Norwegian swimming facilities. The final annual energy consumption (FAEC) was collected from the years 1998 – 2011, and all of the datasets collected were recalculated to match the Oslo climate in 2010, to make them comparable. The data shows a wide variation in FAEC. The findings are compared with corresponding Danish data, which shows a lower FAEC. Relying on the collected data and the assumptions made in this article, the potential reduction of the FAEC in Norwegian swimming pools is estimated to be around 28%.

Introduction

Compared to its population size, Norway possesses a large number of public swimming pools. About 850 pools [1], varying from small school pools to facilities for therapeutic use, sports and leisure are owned and operated by the municipalities. Sources of revenue are normally limited to ticket sales and other means of income, such as cafeterias, private events, etc., and a pool facility is usually heavily dependent on subsidies from the owner, in order to keep it operational. Unlike other building categories, sports facilities are designed in order to meet the requirements of dedicated sports activities, with complex technical support systems e.g., water systems in pools, cooling systems in ice rinks, and advanced HVAC systems. A sports facility can therefore be better described as a processing plant, rather than just as a building. In light of this, other standardized measurements are required to describe the energy efficiency of sports facilities. The consumption of both water and energy may be indicators to describe this deviation from other building categories. Generally, the energy costs of sports facilities represent about 30% of the overall operating costs [2]; when evaluating swimming pools, the share of the energy costs increases even more. The major energy consumers are the heating of water (pool and showers), ventilation, room heating, light systems and the operation of pumps.

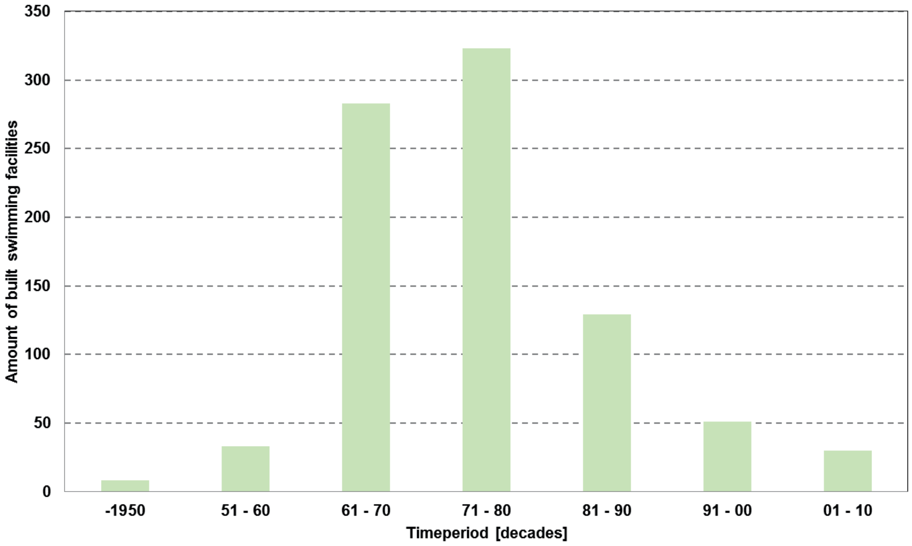

Fig. 1. The number of swimming facilities built in 10-year periods.

The swimming pool facilities in Norway are, on average, 37 years old [1], which means that the construction and technology used is not up to date. About 350 pools had a major refurbishment, which was done approximately 11 years ago [1]. Eliminating the 50 swimming halls built between 1990 and 2010 means that about 450 swimming facilities are currently operating with outdated technology. Taking into account Norway's steadily growing requirement for energy efficiency in the building sector for the last 20 years, there is a strong need to understand the energy systems in sports facilities in general, and in swimming pools in particular. To be able to improve energy efficiency, and make use of this presumed large potential energy savings, it is necessary to determine the actual usage of energy and compare it with new energy efficient swimming facilities.

The average swimming hall in Norway contains of a pool size of 12.5m x 8m with wardrobe and showers. Thermal energy is provided from different sources like district heating, oil fuelled boilers or electricity. Electricity powers lighting, pumps and rotating equipment. In the early years, the typical HVAC system comprised of an air inlet system (blower, heater and filter) and an air outtake system (blower only). Normally no other heating system was installed, as airborne energy was the preferred solution. Thus, no energy recovery (except a partly use of return air), but the indoor climate appeared to be good, as dehumidification was made by use of heated outdoor air, and the pool room normally had negative pressure related to ambience. After 1973 and the oil crisis, awareness of energy recovery rose, and the first generation of integrated packages with heat recovery unit and heat pump was introduced. New and rehabilitated facilities are nowadays equipped with advanced HVAC systems including heat pumps, which allows for energy recovery to air, pool water and tap water. An analysis of the energy-efficiency in over 850 swimming facilities is nearly impossible, and requires a very detailed analysis. The approach taken in this project was to identify the FAEC, and compare it with the FAEC of the most efficient Norwegian facilities, as well as with data from a comparable country. It was an important task to decide which key number to use. The common standard in Norway, for all types of buildings, is to use the FAEC per square meter of usable area (kWh/m² UA) [3], but it may be questionable how useful this is for sports facilities, and especially swimming halls. The varying sizes of entrance areas, locker rooms and showers, as well as, e.g., a cantina, are all disrupting factors that affect this standardized number. The variations in the room climates in different zones of the facility may make the key number inaccurate.

Another option may be to use the water surface (ws) as the reference size (kWh/m² WS), as a substantial part of the energy used in swimming facilities is related to the water area (heating of water, evaporation, pumps, etc.). The Danish Technological Institute [4] has selected this key number as well. A diagram describing the energy consumed in swimming facilities can be found in a book from Sintef Byggforsk [5]. The annual energy consumption in 27 swimming pools for one year is shown, using kWh/m^2_{UA} as the measurement unit. This diagram can also be found in the work from Martin Øen [6] who added a curve for the FAEC in kWh/m² WS to the curve using kWh/m² UA (Fig. 2) to compare them. There is a substantial difference between these two key numbers. This study uses kWh/m² WS, making a comparison to the energy data from the Danish Technological Institute possible. The deviation in performance by use of the different key numbers calls for more research with respect to determining a more representative one for FAEC in pool facilities. The only energy statistics available for Norway include the data from one year, for 27 swimming facilities [5], as mentioned above. This situation is not satisfactory, especially considering the large number, and the age of these facilities in Norway. The aim must be to establish a statistical database in order to evaluate the current status, and determine a possible direction of improvement of design and operation.

It is also interesting that there is not much data published concerning FAEC of swimming halls. In a book from Saunus [7] an FAEC of 7 240 600 kWh got reported for a spa in the north of Germany which equals 5984 kWh/m² WS. Finnish researchers [8] computed the annual energy use of one swimming facility with 636 kWh/m² UA which corresponds to 4475 kWh/m² WS and Trianti-Stourna et al. [9] describe the FAEC for swimming facilities located in Mediterranean climate with 4300 kWh/m² WS while it is about 5200 kWh/m² WS for facilities located in continental climate. Data from British swimming facilities is available as well and shows an FAEC of 1573 kWh/m² UA for “typical practice” and 725 kWh/m² UA for “good practice” [10].

More on factors influencing FAEC with respect to evaporation [11, 12, 13], heat pumps [14, 15, 16] and heat demand [17] are available.

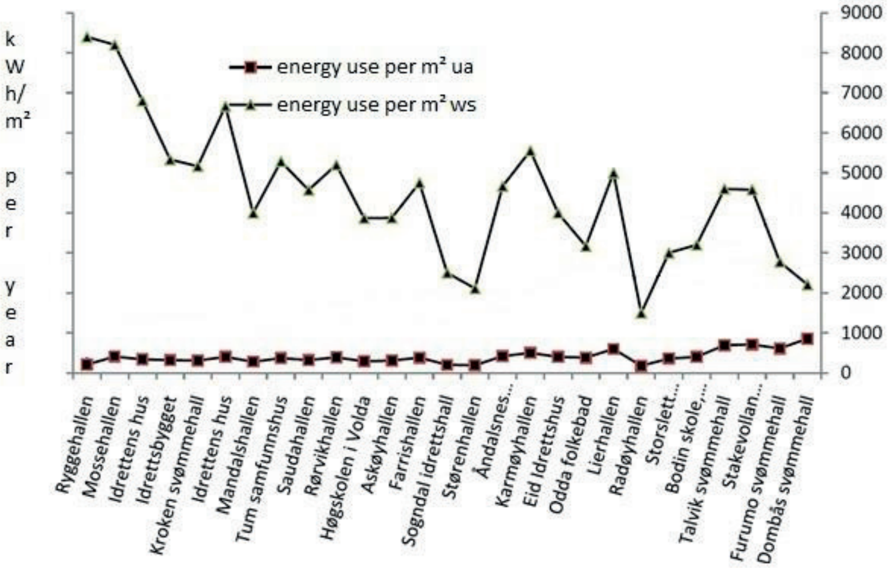

Fig. 2. FAEC in kWh/m² UA in comparison with kWh/m² WS [6].

Method

A total of more than 250 datasets (one dataset is defined as the FAEC from one swimming hall for one year) was collected with the help of a questionnaire. More than one third (37%) of the answers could not be used due to inaccuracy, missing data or the lack of energy measuring devices at the facilities. The two main questions were about the FAEC in kWh and the WS, to be able to calculate the desired measurement unit (kWh/m² WS). The statistical analysis in this paper includes data from 41 different swimming pool facilities in Norway from the years 1998 to 2011. All data included are recalculated to match the Oslo climate in 2010 using the equation from Enova [18]:

$$Energy\,use_{Oslo} = Energyuse_{actual\,facility}\left((1-0{,}4)+0{,}4*\left(\frac{Degreedays_{Oslo}}{Degreedays_{actual\,facility}}\right)\right)$$

The Norwegian degree-days originate from Enova's website [19], whilst the Danish data was retrieved from Denmark's meteorological institute [20].

The FAEC (in kWh) was divided by the area of water surface (m² WS) to achieve the desired measurement unit, accounting for one dataset. These datasets were divided into different categories, which are supposed to influence the energy consumed (for example, different categories of WS and year built).

The data was not divided into groups with respect to different HVAC systems, operating hours, water temperature, etc. because of lack of available reliable data. None of the facilities are exactly the same and dividing them into detailed groups would make a statistic analysis impossible.

Results

Figure 3 shows the FAEC in kWh/m² WS for all swimming facilities over all available years. It is evident that the energy consumed varies significantly between the different buildings. The lowest values are slightly below 1000 kWh/m² WS per year, while the highest value is almost 11.000 kWh/m² WS per year.

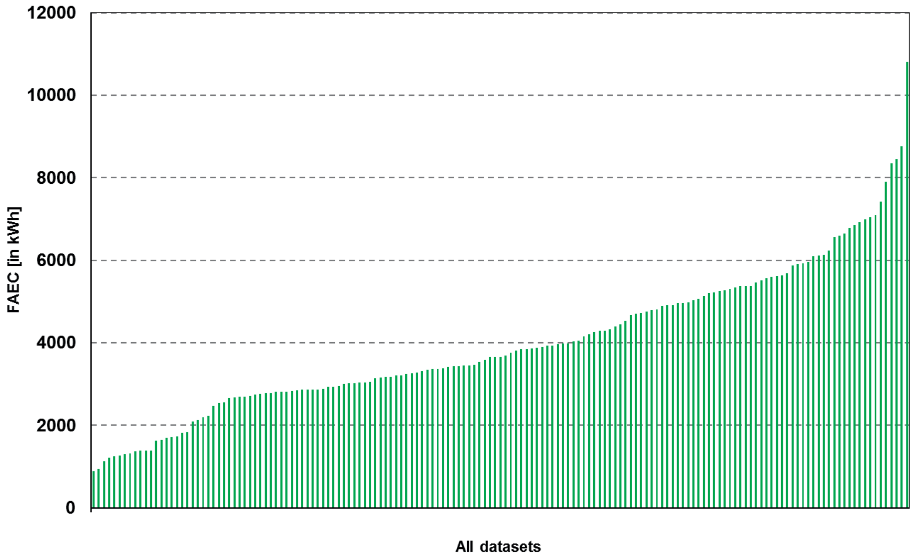

Fig. 3. FAEC (in kWh/m² WS) for all included datasets sorted from smallest to largest.

The average for all the datasets is 3991 kWh/m² WS per year, with a standard deviation of +/- 1757 kWh/m² WS). As not all swimming pools could provide an equal number of datasets, an average for every swimming facility was calculated to prevent a skewing of the data. The average FAEC for the years reported is 4004 kWh/m² WS with a standard deviation of 1821 kWh/m² WS. In order to analyze the data more accurately, and to take the different sizes of the facilities into account, the swimming pools were divided into three different categories:

1 - Facilities with up to 300m² WS
2 - Facilities with 301 to 600 m² WS
3 - Facilities with more than 600m² WS

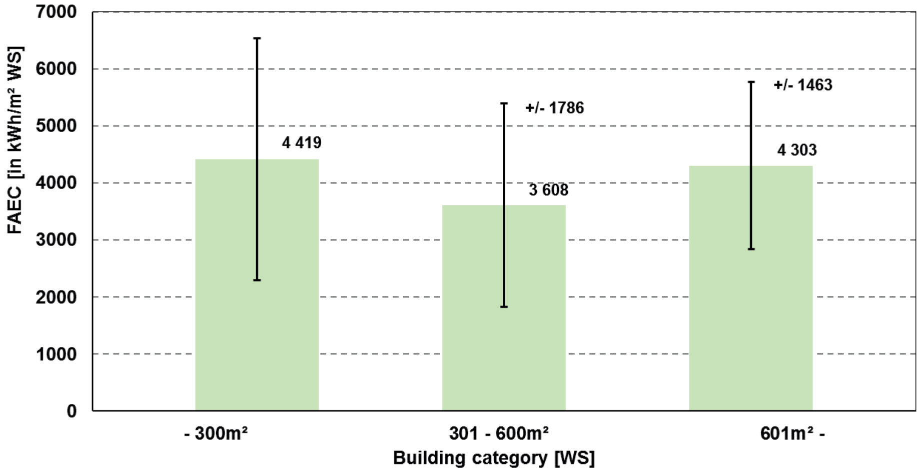

Fig. 4. FAEC in kWh/m² WS per category with standard deviation.

As can be seen from figure 4, the smallest swimming halls (- 300 m² WS -) use the most energy, while the category 301 – 600 m² WS shows a 804 kWh/m² WS lower average. The third category, consisting of the facilities with more than 600 m² WS, has a FAEC which is 116 kWh/m² WS lower than the one of category 1.

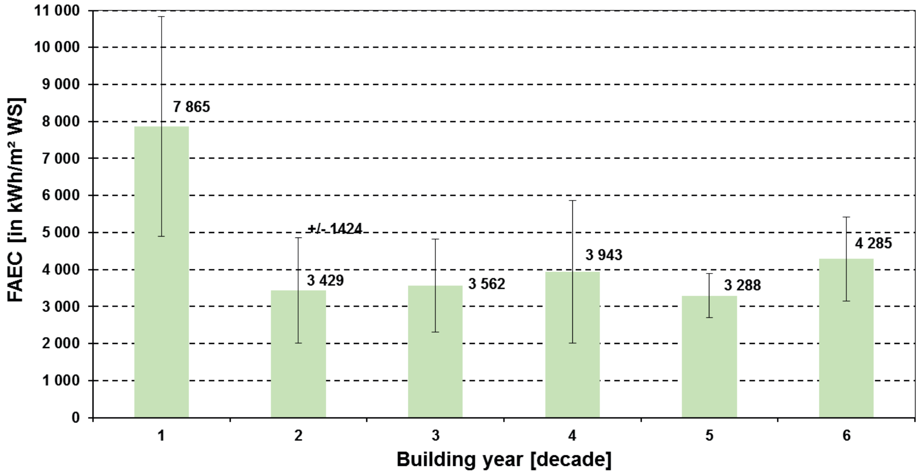

Fig. 5. FAEC in kWh/m² WS in relation to building year in decades

It is also interesting to look at the FAEC, sorted by the decades of the building year (figure 5), as this can be used as a parameter for both the age and the technology used.

The facilities were grouped in age by decades, and the average FAEC and the standard deviation was calculated. The period from 1950 until 1960 showed the highest value with the periods from 1960 until 2000 approximately 4000 kWh/m² WS below. The last decade shows a slightly higher FAEC.

Discussion

Figure 3 shows a large variation in the FAEC within the different swimming facilities. It is a difficult task to collect accurate data on this area, especially data that can be trusted. A number of answers from the questionnaire could not be used, as the results were either inaccurate or too improbable. A major problem seems to be the use of energy measurement devices in the facilities. A lot of swimming halls are combined with sports halls, schools or culture halls, and do not have separate energy meters for each of them. The large variety in FAEC, as well as the large standard deviations, could be an indication of inaccurate measurements. This error source is hard to estimate, and should be taken into account. The findings call for the future regular collection of energy data, in order to train and educate the operators to install energy meters dedicated to the different sections of the buildings.

Another source of error could be dividing all swimming halls in only three groups by size. The facilities differ in opening hours, water temperature and consumption, HVAC systems, age and visitors.

Looking at the three categories concerning the WS, it was expected that the smallest buildings would have the lowest FAEC, but this category consumes the most of all three. An explanation can be found looking at the periods of construction within the categories. The first category (up to 300 m² WS) has an average age of 39 years, while the buildings in category 2 (301 – 600 m²) are 34 years, and the third category showed an average of 22 years. Old buildings imply old building codes and old technology, which reflects the high FAEC. The energy consumed for the second category in the middle shows a lower FAEC which can be explained by the age as well, but the largest category doesn't really fit into this paradigm. Following this line of argument, it should show the lowest FAEC as it contains the newest buildings. But again, looking behind the results these large buildings are, in most cases, more complex pool facilities. They have pools with artificial waves, flow channels, saunas, steam baths and often very large glass facades that allow the visitors to enjoy the landscape outside. All these factors increase the FAEC.

Figure 5 shows mostly predictable results. Very high values for the buildings built before 1960, which is due to old building techniques and technology standards. The results for buildings built in the 1960s show a large decrease, which can be explained with more advanced technology, stricter building codes and more experience in the building sector.

The ups and downs from the 1960s until the 1990s are most likely random and evolve from different building sizes, different technology used and different practice.

The high FAEC for buildings built after 2000 was not initially expected, as they should have been built with more energy awareness, using the latest technology. But as stated before, these new buildings fall into the category of very large swimming facilities, and have a lot of additional services for their customers which consumes large amounts of energy.

Tab 1: Potential for energy efficiency improvement in Norwegian swimming halls

	-300 m²	301 - 600 m²	601- m²
Total average	4419	3608	4303
Average better half	3054	2278	3246
% difference to total	31	37	25
Average best third	3008	2002	2840
% difference to total	32	45	34
Danish average	3611	2847	2276
% difference to total	18	21	47
% difference to 1/3	-20	-42	20
% difference to 1/2	-18	-25	30
best third	3008	2002	2840
middle third	3983	2278	4201
worst third	6777	5390	5586

The potential in terms of saving energy is hard to estimate, but a look at the standard deviations shows a large variation, and it should be possible to converge towards the “good” swimming facilities. The average for the best third and the better half of each category can be seen in table 1, as well as the percent value if compared to the Norwegian average.

The difference between the Norwegian average FAEC and the average of the best third is very high. Easing the criteria to the better half of each category shows only slightly better results, which confirms the huge potential concerning energy saving.

Figure 6 shows the results graphically, and it can be seen that there is only a minor difference between the average values of the better half compared to the average of the best third. This is an indicator for the large diversity in the use of energy in swimming halls, and confirms the substantial variations of FAEC from the collected data.

To make an even deeper analysis, the average of the annual energy consumed was divided into thirds for every category, as can be seen in Figure 7. The average for the worst third is very high and definitely needs to be reduced. The difference between the averages of the middle and the best third is not that large; therefore, it seems reasonable to try to lower the FAEC of the worst third to the level of the middle third.

Another factor proving these findings is the comparison with the Danish statistics. They originate from the website of the Danish Technological Institute [4], where they are publicly accessible. The diagram in figure 8 shows the Norwegian and Danish values, compared for each of the three categories. As mentioned in the methods, all values are corrected to match the Oslo climate in 2010, making them comparable.

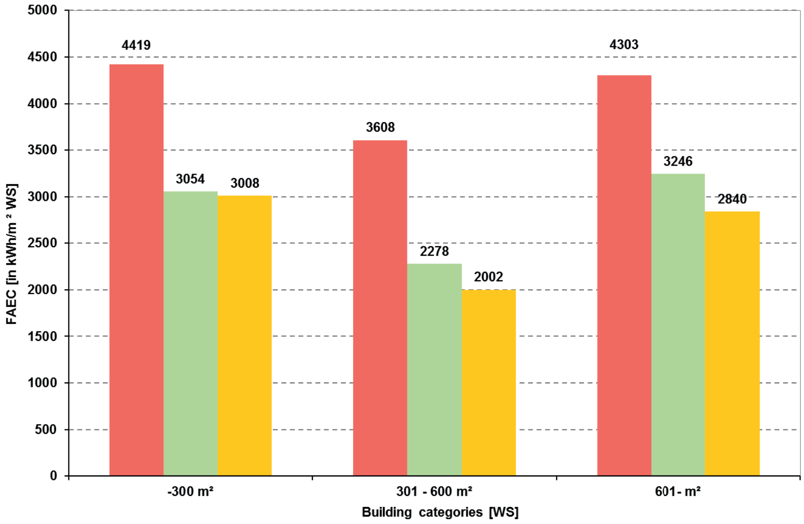

Fig. 6. Average of the total (red), the better half (green) and the best third (orange) of FAEC in kWh/m² WS in Norwegian swimming halls, per category.

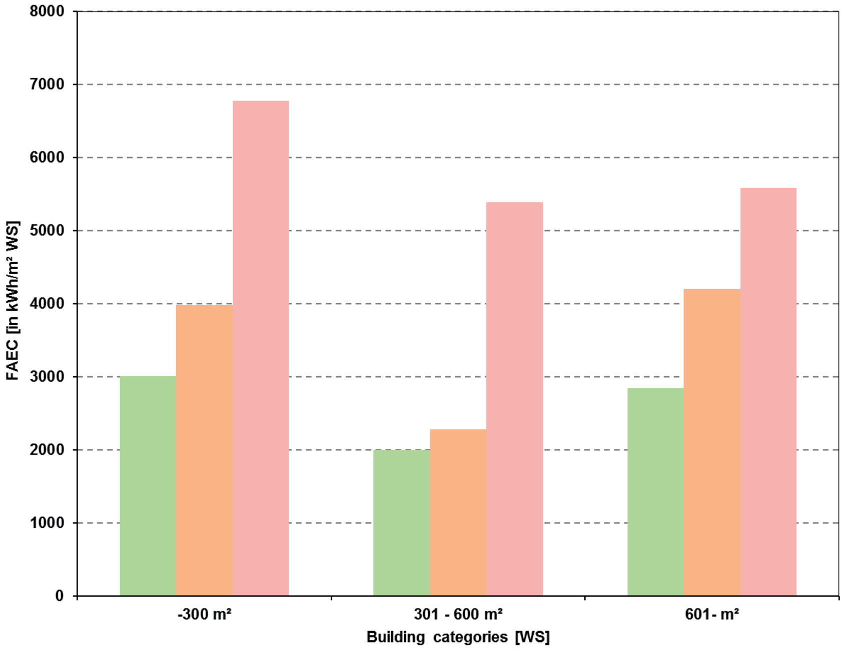

Fig. 7. Average of the FAEC in kWh/m² WS of the best (green), middle (orange) and worst third (red) of the different categories.

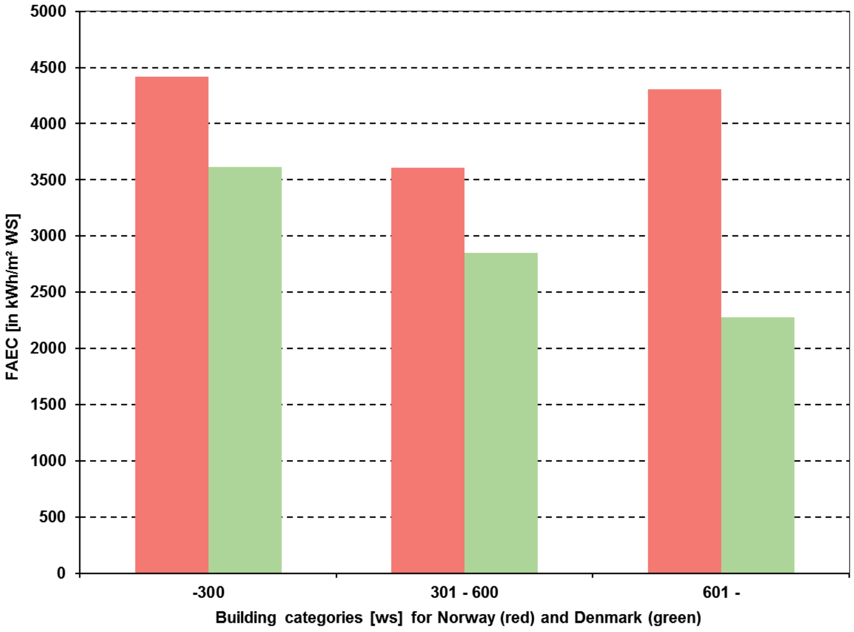

Fig. 8. Comparison between Norway (red) and Denmark (green) of FAEC in kWh/m² WS per category.

The Danish swimming facilities in category 1 use 808 kWh/m² ws less per year than the Norwegian ones. The difference is about the same, with 761 kWh/m² WS per year if comparing to the buildings in category 2, which have a WS of 301 – 600 m². The largest potential, if compared to Danish facilities, can be found in the third category (swimming facilities with more than 600 m² WS). With 2027 kWh/m² WS per year, the Danish facilities use almost 50 % less energy.

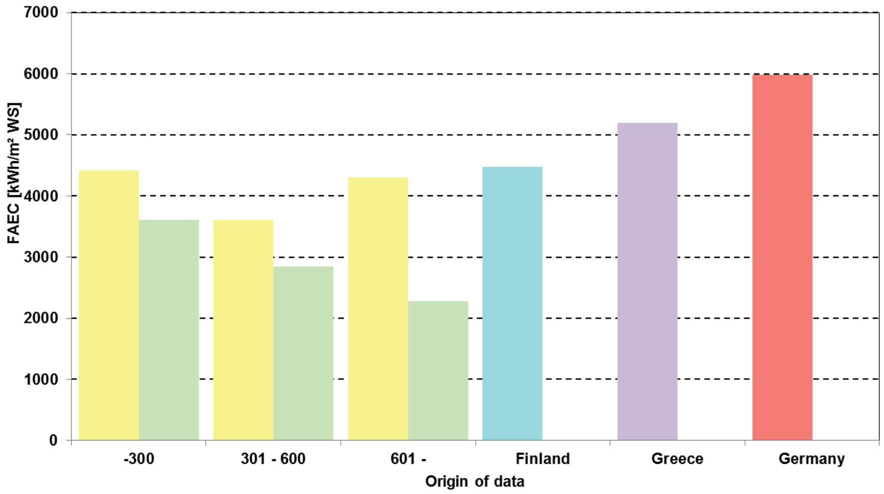

Fig. 9. Comparison between different countries of FAEC in kWh/m² WS [Norway (yellow), Denmark (green), Finland (blue), Greece (purple), Germany (red)].

The Danish data sets are an important estimator of how realistic the analysis is, based on Norwegian data. The Danish facilities in category 1 use, on average, 18% less energy per year than the Norwegian. To expect an FAEC reduction of 31 % (compared to the best half) or 32 % (the best third) could mean aiming too high, but the potential improvement is still significant, with about 25 % (mean of the average of the Norwegian better half and the Danish total average). The difference increases when analyzing the group for 301 – 600 m² WS. The FAEC of the Danish swimming facilities is 21 % lower than that of the Norwegian ones. Here as well, the estimations of 37 and 42% (compared to the best half and the best third) improvement seem too high, but a possible improvement of 29 % is very satisfying. The largest Danish facilities continue with the trend, using about half of the energy (-47 %) of the Norwegian. In this case, the estimate of saving about 36 %

seems realistic. The average energy consumed by the best third of the Norwegian facilities still uses 564 kWh/m² WS more per year than the Danish ones. In general, it can be said that the swimming halls in category 1 have the largest potential, as they make up the largest share of all Norwegian halls (about 550 of 850), followed by the medium big halls (280 of 850). The largest category has the highest saving potential, with 36%, but as there are only about 20 such halls in Norway, the total amount of savings will not be very high.

Conclusion

By estimates from the underlying statistics, the FAEC for all the 850 Norwegian swimming pools is roughly in the range of 883 GWh/year. Provided that the assumptions about saving potential are approximately correct, and using the average FAEC of the difference between Danish and Norwegian swimming halls, and the difference between Norwegian halls and the best 50%, this would mean the yearly FAEC in Norwegian swimming halls could be reduced by about 28%, or 246.5 GWh/year.

As expected, a large variation in the FAEC is identified in Norwegian swimming pools, which implies an equal potential for saving energy as well as money. The analysis of both the Norwegian and the Danish data sets seems to confirm this trend. A detailed analysis of the most efficient swimming pool facilities is required to better understand the variation of FAEC in the different functions within each facility. Furthermore, the objective must be to identify the most wasteful sources in the buildings with high FAEC, and apply new technologies in order to improve their energy efficiency.

References

[1] Kulturdepartement, Anleggsdata - regjeringen.no, http://www.regjeringen.no/nb/dep/kud/kampanjer/idrettsanlegg/anleggsdata.html?id=612410 (accessed 29.05.12).

[2] Great Britain: Energy Efficiency Office, Introduction to Energy Efficiency in Sports and Recreation Centres, http://www.targ.co.uk/other/guide78.pdf (accessed 20.08.12).

[3] Statistisk sentralbyrå, Energibruk i bygninger i statlig forvaltning, http://www.ssb.no/emner/01/03/10/entjen_statres/tab-2009-12-15-01.html (accessed 29.05.12).

[4] Danish Technological Institute, Nøgletal, energi- og vandforbrug i svømmehaller, http://www.teknologisk.dk/21324 (accessed 29.05.12).

[5] T. Bøhlerengen, J. Mehus, A. Waldum, P. Blom, T. Farstad, Byggforsk håndbok 52: Bade og svømmeanlegg, Norges Byggforskningsinstitutt, Oslo, 2004.

[6] M. Øen, Indoor swimming pools and requirements for energy efficiency, NTNU, Trondheim, 2010.

[7] C. Saunus, Schwimmbäder, Planung - Ausführung – Betrieb, Krammer Verlag Düsseldorf AG, Düsseldorf, 2005.

[8] A. Saari, T. Sekki, Energy Consumption of a Public Swimming Bath, The Open Construction and Building Technology Journal, 2 2002 – 206, 2008

[9] E. Trianti-Stourna et al., Energy conservation strategies for sports centers: Part B. Swimming pools, Energy and Buildings, 27 (2) 123-135, 1998.

[10] Amateur Swimming Association, Use of energy in swimming pools, http://www.swimming.org/assets/uploads/library/Energy_in_swimming_pools.pdf (accessed 20.08.12).

[11] M. M. Shah, Improved method for calculating evaporation from indoor water pools, Energy and Buildings, 49 306 – 309, 2012.

[12] F. Asdrubali, A scale model to evaluate water evaporation from indoor swimming pools, Energy and Buildings, 41 (3) 311 – 319, 2009.

[13] M. M. Shah, Prediction of evaporation from occupied indoor swimming pools, Energy and Buildings, 35 (7) 707 – 713, 2003.

[14] P. Sun, et al., Analysis of indoor environmental conditions and heat pump energy supply systems in indoor swimming pools, Energy and Buildings, 43 (5) 1071-1080, 2011.

[15] L. Johansson, L. Westerlund, Energy savings in indoor swimming pools: comparison between different heat-recovery systems, Applied Energy, 70 (4) 281 – 303, 2001

[16] L. Westerlund, J. Dahl, Use of an open absorption heat-pump for energy conservation in a public swimming pool, Applied Energy, 49 (3) 275 – 300, 1994.

[17] L. Westerlund, J. Dahl, L. Johansson, A theoretical investigation of heat demand for public baths, Energy 21 (7-8) 731 – 737, 1996.

[18] Enova, Enovas byggstatistikk 2010, http://www2.enova.no/publikasjonsoversikt/file.axd?ID=594&rand=33fc85df-11da-4041-8d7c-e530c6104371 (accessed 20.08.12).

[19] Enova, Graddagstall – Enova, http://www.enova.no/radgivning/naring/praktiske-ressurser/bygningsnettverket/graddagstall/290/0 (accessed 29.05.12).

[20] Danish Technological Institute, DMI - Vejret i Danmark. http://www.dmi.dk/dmi/index/danmark.htm (accessed 29.05.12).

Paper II

Kampel, W., Aas, B. and Bruland, A. Energy performance indicators for a reliable benchmark of swimming facilities. Submitted on 10.08. 2015, under review.

Energy performance indicators for a reliable benchmark of swimming facilities

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Abstract

The main research question is which energy performance indicator should be used to benchmark energy use in swimming facilities. A quality check was applied to the collected data resulting in 176 datasets. A correlation and multiple linear regression analysis was carried out to identify (i) how strong a number of variables characterizing swimming facilities are singularly related with the energy performance and (ii) how the identified variables can together explain the variation of energy performance. Differently from residential and commercial buildings, climate does not drive the total energy performance of swimming facilities. Instead, water usage was found to be most strongly correlated with the energy use, followed by the number of visitors, the usable area and the water surface. It is difficult to obtain accurate values for any of these variables except for the water surface. A multiple linear regression analysis showed that the number of visitors is the variable that explains most of the variation of the energy performance of swimming facilities. Therefore, the authors conclude that, for benchmarking purposes, the energy use of swimming facilities, shall be preferably normalized with respect to the number of visitors. If no reliable visitor count is available, water surface can be used.

Keywords

Benchmarking, buildings, energy efficiency, energy use, energy performance indicator, swimming facilities.

Introduction

Buildings account for approximately one third of worldwide energy use [1, 2]. A building category that has received little attention in the literature is sports facilities where especially ice rinks and swimming facilities stand out with high use of energy [3]. Figure 1 shows the average delivered energy (DE) for the ten largest building categories in Norway [4]. Basically, energy use in sports facilities can range between 150 kWh/m² per useable area (UA) and 300 kWh/m^2_{UA}, and swimming facilities are reported to use even between 400 kWh/m^2_{UA} and almost 1 600 kWh/m^2_{UA} [3, 5-9].

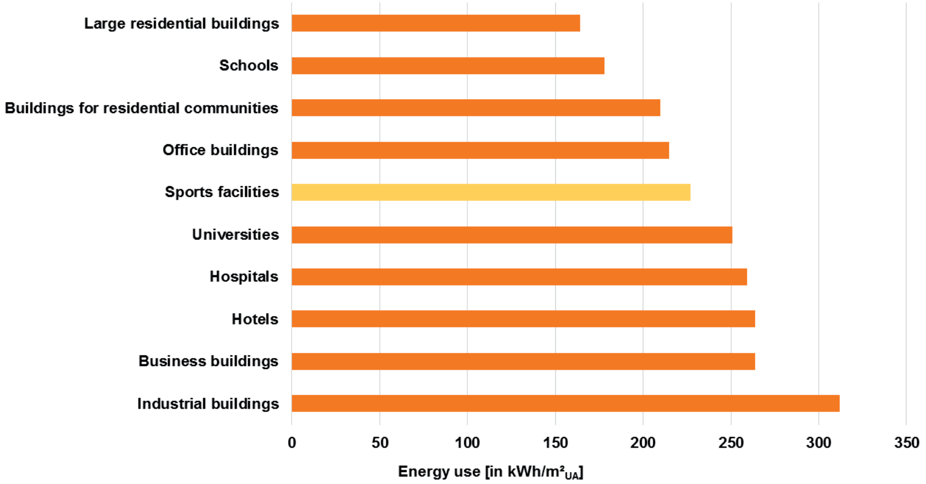


Figure 1: The annual energy performance [10] of the ten largest building categories in Norway expressed in DE normalized with respect to UA (kWh/m^2_{UA}) [4].

Generally speaking, high energy use in buildings is related to weaknesses in building design and maintenance [11, 12]. To identify and eliminate possible flaws [13] and to push towards more sustainable solutions [14], energy benchmarking is an useful measure. Benchmarking energy use of buildings serves two main purposes. First, energy classification is important to compare similar buildings, which can encourage owners to improve energy efficiency in their buildings. Second, energy performance diagnosis is the next step of an energy analysis. While the energy classification indicates the performance of a whole building, the energy performance diagnosis provides more detailed information and can allow to detect the causes of energy losses [13].

The Directive of the European Parliament and Council on the energy performance of buildings, published in 2002 [15] and recast in 2010 [16], requires all Member Countries of the European Union to introduce laws for the regulation and energy certification of buildings [17]. To monitor the effect of these policies, significant energy performance indicators (EPIs) are essential [13]. This is especially important for energy intensive building types [18].

There are accepted EPIs for the majority of building types, but there is almost no reasoning or discussion about whether or why these EPIs are the best to use [18]. Further, Goldstein & Almaguer [19] emphasize that EPIs should be meaningful and easy to derive and explain. In addition, to the knowledge of the authors, no papers have been published regarding benchmarking of energy use in swimming facilities. Some publications address improving energy efficiency in swimming facilities, but none of them states anything about which indicator to use and why [7, 20-22].

Literature review

To describe the energy performance of swimming facilities, most statistics and publications normalize the energy use with respect to the usable area, kWh/m^2_{UA}, [3, 5-8, 23, 24] and/or to water surface (WS), kWh/m^2_{WS} [3, 7-9, 23, 25-27].

Statistics Norway reported that 21 Norwegian swimming facilities had an average DE of 280 kWh/m^2_{UA} [24]. This is, to the authors' knowledge, the lowest reported value. In a publication from Bøhlerengen et al. [5], the DE of 27 Norwegian swimming facilities varies between 180 kWh/m^2_{UA} and 860 kWh/m^2_{UA} with an average of 401 kWh/m^2_{UA}. In a third Norwegian publication, Røkenes [8] has investigated three swimming facilities in the Oslo area reporting an average DE of 515 kWh/m^2_{UA}. A report from the Swedish municipalities [3] is in accordance with the findings of Bøhlerengen et al. [5] showing that 17 Swedish swimming facilities have an average DE of 403.4 kWh/m^2_{UA}. The five Greek swimming facilities investigated by Trianti-Stourna et al. [7] were found to have a slightly higher average with 450.1 kWh/m^2_{UA}. British swimming [6] reported 725 kWh/m^2_{UA} for good practice and 1 573 kWh/m^2_{UA} for typical practice without specifying the reference features of a good or typical facility.

A main issue with comparing the described data is that most of the authors do not properly describe the included facilities. Indeed, only the scientific papers of Røkenes [8] and Trianti-Stourna et al. [7] comprehensively describe their sample. Data from Statistics Norway [24], Bøhlerengen et al. [5] and from the Swedish municipalities [3] do not include essential data to compare buildings' performances.

Another factor making it difficult to compare the DE of swimming facilities is the use of different EPIs. While the above mentioned sources used kWh/m^2_{UA}, several publications [3, 7-9, 26, 27] use kWh/m^2_{WS} or both of them. While the lowest average value of 1 302.7 kWh/m^2_{WS} is reported by Swedish municipalities [3], the highest average value was 4 481 kWh/m^2_{WS} found by Øen [26] using the dataset from Bøhlerengen [5]. In this context, it is also interesting to analyse the ratio of WS and UA for the articles expressing DE with both discussed EPIs. Swedish municipalities [3] found the UA to be 3.23 times larger than the WS, representing the lowest reported ratio while the data published by Bøhlerengen [5] and analysed by Øen [26] shows the highest ratio with 11.17. Trianti-Stourna et al. [7] and Røkenes [8] reported values between them with 3.43 and 7.57, respectively.

With the literature research as background, it is not possible to identify which EPI should be used for a benchmarking purpose. No investigations are published showing relationships between UA or WS with DE. Additionally, Øens [26] data show a large spread, no matter which EPI is used.

The most used EPI for buildings is kWh/m^2_{UA}, which can be problematic when used for swimming facilities. The data will be skewed if, for example, leisure pool facilities are compared with smaller swimming facilities. The EPI has to be chosen in a way to make buildings comparable and to use the data as basis for energy certification and a further energy performance diagnosis. Using common building EPIs may be less accurate for swimming facilities because of their characteristics:

- Temperature and humidity level in the pool room:
  The swimming pool hall holds typically around 30 °C with relative humidity at about 55 % - 60 %. Besides the additional energy needed for space heating the dehumidification process differs significantly. In a swimming facility, dehumidification is also active during winter. The few residential and commercial buildings that possess a dehumidifier, aim to humidify the space during winter.

- Evaporation due to pool usage:
  The evaporation from the pool surface is a phenomenon specific for swimming facilities and establishes a substantial energy transfer between the water treatment system and HVAC system. If the HVAC system does not include a heat pump, the energy in the humid air may only be recovered to a limited extent.

- Warm water use for pools and showers:
  Energy demand for warm water is common for different building categories. The water consumption per person as reported by Kampel et al. [25] is 107 l for the most effective swimming facilities. The average for all swimming facilities can be expected to be around the average water use per person per day in European residential buildings of 160 l per person and day [28] The difference is that the water consumption in swimming facilities is mostly warm water thus increasing the energy use.
- Installation of a water treatment system:
  Pool water must be circulated in order to maintain temperature and water quality. Rate of circulation is to a certain extent related to visitors. Residential and commercial buildings do not use a comparable water treatment system.
- Users' behaviour:
  Visitors shower twice and pollute the water when using a swimming facility, which increases energy use. Despite that, evaporation is increased significantly because of turbulences in the water and increased wet surface (wet bodies and sprays on the floor). Users of residential or commercial buildings do not have the same impact on energy use as in swimming facilities.
- Variety of services provided:
  On one end of the scale there are very small swimming facilities with one little pool while there are leisure pool facilities on the other hand. They provide additional attractions like wave pools, sprays, waterfalls or flow channels. Their offer might also include sauna, solarium or training centres.
- Yearly operating hours and their pattern.
  Offices for example are typically used for 50 to 60 hours per week 11 to 12 months a year. Swimming facilities can be open only for two or three months or the whole year. Some are operational for a few hours per week while other are opened for up to 100 hours each week.

These characteristics show that a large part of the energy usage of swimming facilities is used for different reasons and uses when compared to other building types. Therefore, swimming facilities appear to be better described as process plants rather than buildings [9], and another methodology should be used to describe their energy performance.

Benchmarking of process plants of energy-intensive industries is described by Saygin et al. [29]. Energy and output data are combined to form the EPI (used energy/output). Pérez-Lombard et al. [30] suggest the same procedure.

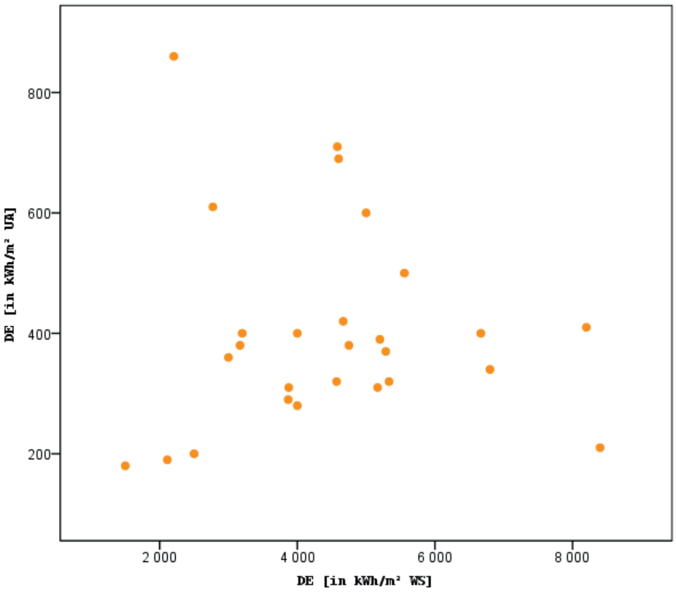


Figure 2: Scatter plot of the DE of 27 swimming facilities expressed in kWh/m$^2_{UA}$ (y-axis) and kWh/m$^2_{WS}$ (x-axis). Data from Bøhlerengen et al. [5].

Swimming facilities are designed to provide sports and recreation activities for the public and athletes. When defining them as process plants, the output parameter is the number of visitors served in a given period, but to the knowledge of the authors, there is no data published using kWh/visitors as EPI.

Based on the literature review, it can be reasoned that there is no consensus on which EPI should be used. Øen [26] analysed data from Bøhlerengen [5] and showed that the choice of EPI is important by comparing the two most used EPIs (kWh/m$^2_{UA}$ and kWh/m$^2_{WS}$). It can be observed that some swimming facilities, which seem to perform well when using kWh/m$^2_{UA}$, perform weakly when using kWh/m$^2_{WS}$ (Figure 2).

The purpose of this article is to validate the most used EPIs, investigate factors influencing energy use and determine which EPI provides the best fit.

Methodology

In general, the objective of a performance indicator is to provide a quick overview of a given performance of a system. This paper deals with expressing the energy performance through a suitable EPI. In this case, the system is a swimming facility considered as a whole and not its individual subsystems, such as its building envelope or technical systems. Therefore, the functional formulation of the problem is

$$EPI = \frac{Energy\ used}{Normalisation\ metric(s)}$$

Energy used is a function of quantities like time period, size of the building, technical systems, services offered, number of visitors etc. Normalisation metrics are quantities that can be measured and explain (even partially) a given performance of the analysed system.

Selection of suitable metrics

The following two sections include a discussion about which variables to use in the functual formulation of the problem.

Metric for expressing energy use

This article focuses on the swimming facility as a system comprising the building envelope and its installations. Therefore, fixing the control volume of the analysis on the building site, the most appropriate metric to express the energy performance is DE, which aggregates energy uses per energy carrier. This choice is also supported by a practical reason: all facilities have, at least, a general meter per each energy carrier entering the control volume and energy uses can be easily collected through on-site measurements and energy bills. For these reasons the authors pursue using DE throughout the paper. DE is defined in European [10] and international standards [31].

Nevertheless, primary energy (PE) is suitable to be used if the control volume is expanded to assess the source energy footprint of a swimming facility. Unfortunately, PE cannot be collected through on-site measurements and strongly depends on "the method used to calculate site-to-source electricity energy factors. National averages do not account for regional electricity generation differences […], for hourly variations in the heat rate of power plants or how utilities dispatch generation facilities for peak loading. Electricity use at night could have fewer source impacts than electricity used during the peak utility time of day" [32]. In case PE is used, the authors strongly recommend to accompany the EPI with the site-to-source energy conversion factors adopted for the calculation.

Normalisation metrics

The investigated variables to be used as normalisation metrics were chosen because they influence energy flows and/or some of the swimming facilities' processes:

- *Usable area* characterises the spatial extent of a building. It corresponds to the *intra muros* area defined in ISO 9836 [33] and the variable `UA` has been defined in the database.

- *Water surface* characterises more specifically a swimming facility and, in this context, is more specific than UA and can be calculated with a higher accuracy. The term used in the article is equal to the *pool surface area*, where attractions (e.g., slides, sprays etc.) are not included. It is described with the variable `WS` in the database.

- The *age of the buildings* is an indicator for the technical quality of the building envelope and installed systems' technology. It is defined with the variable `Age` in the database.

- Average water temperature is the average temperature of different pools weighted by their WS. The higher the temperature the higher the expected energy use. It is described with the variable `AWT` in the database.

- *Yearly operating hours* is defined as the cumulative number of hours when a given facility is in operation in a year. The more hours a facility is operative the higher the assumed energy use. It is described with the variable `YOH` in the database.

- Visitors trigger several mechanisms (e.g., hot water demand, evaporation etc.), which lead to an increase in energy use. The cumulated number of visitors that use a given facility in a year is described with the variable `Visitors` in the database.

- *Water usage* is the overall amount of water used in a given facility to wash filters and for sanitary usage. It is expected to increase energy use as energy is needed to heat water. It is described with the variable `WU` in the database.
- The *degree-hours for heating* are often used to express the severity of the climate of a given location, which is assumed to influence energy use for space heating. Here, due to the specificity of the Norwegian climate, we refer to just space heating and use a base temperature of 17 °C [34]. It is described with the variable HDD_{17} in the database.

Data collection

After having identified reliable metrics, a questionnaire has been specifically built [25] and sent to all the Norwegian provinces, which passed the questionnaire on to their communities and finally to the swimming facilities. The facilities that were not owned or operated by the public sector were contacted directly. The questionnaires were handled by operators, chief engineers and utility managers.

In total, almost 300 datasets (one dataset is defined as an array composed of the DE for one year for one swimming facility with the corresponding variables) were collected. A quality check was performed on the datasets. It consisted in verifying the completeness of the data stored in each array, the order of magnitude of delivered data, cross-comparison of questionnaires, design documentation and information collected during inspections. However, after the procedure, approximately one third of the datasets could not be used due to inaccuracy, missing data or the lack of dedicated energy-meters installed in the facilities. Accordingly, 176 datasets from 43 swimming facilities representing approximately 5 % of the 848 swimming facilities in Norway were used for the statistical analysis [35].

Statistical analysis

After (i) having identified suitable metrics to express energy use of swimming facilities and to normalize it, (ii) having collected datasets from several Norwegian swimming facilities in a database, and (iii) having operated a quality check of the data stored in the database, a statistical analysis was carried out by performing a correlation and a multiple linear regression analysis in order to identify (i) how strongly a number of variables characterizing swimming facilities (`UA`, `WS`, `WU`, `Visitors`, `YOH`, `HDD`$_{17}$, `Age` and `AWT`) are individually related with their energy performance and (ii) how the identified variables can together explain the variation of the energy performance of a swimming facilities.

The purpose of the paper is not to establish cause-and-effect relationships, but to assess in what extent a set of variables are associated with each other. For this reason, the authors studied the collected data with correlation and linear regression analysis. Statistical analysis was performed using the statistical software package IBM® SPSS® Statistics, version 22.

Univariate analysis of the database

A univariate analysis was carried out to describe the distribution of the values of each variable stored in the database. They are represented by boxplots (Figure 4).

Correlation analysis

A correlation coefficient is a measure of linear association between two variables. In order to determine an empirical relationship between DE and the identified normalisation metrics, the bivariate analysis is adopted. The Pearson product-moment correlation coefficient was not used as the investigated variables are not normally distributed (Kolmogorov-Smirnov test, Histograms), which is a condition to apply it to the variables [36, 37]. Kowalski stated that Pearson's correlation coefficient "…may be quite sensitive to non-normality and that normal correlation analyses should be limited to situations in which (X, Y) is (at least very nearly) normal." [38]. Therefore, Spearman's rank correlation was applied as "it is a measure of a monotone association that is used when the distribution of data makes Pearson's correlation coefficient undesirable or misleading” [39]. Spearman’s method prescinds the data as it uses ranks instead of the absolute numbers and provides estimation of how well a monotonic function represents a relationship between two ranked variables. For a better understanding of the spread, scatter plots were created (Figure A.1), which can be found in the Appendix.

Multiple linear regression analysis

A multiple linear regression analysis was applied to investigate to what extent the normalisation metrics can explain DE. It is worthy to mention that the linear regression technique does not test whether data are linear distributed; on the contrary, it assumes linearity between the dependent variable (DE) and one or more independent variables (the normalizing metrics).

Therefore, scatter plots have been reported in the Appendix to check if data were affected by un-negligible non-linearity. Then, the non-existence of multicollinearity among the set of independent variable was tested. UA, WS, YOH, WU and Visitors correlate highly with each other, and all but one of those variables had to be excluded.

To investigate which variable influences DE the most and therefore should be used as normalisation metric, it is important to understand the mutual interactions between the investigated variables. When performing the multiple linear regression analysis, finding multicollinearity was expected. UA and WS are indicators for the size of the building and are correlated with each other (Table 1). The higher these physical parameters, the more visitors the facility will host. WS shows a higher correlation coefficient than UA to Visitors (Table 1), which can be explained with the uncertainty connected to UA. This uncertainty has its origin in multipurpose facilities where, e.g., changing rooms, entrance area and showers are shared between a swimming facility and a handball hall. Despite that, some of the operators include the technical areas when reporting UA and some not, leading to distortion.

The relation between Visitors, UA and WS is also influenced by YOH (Table 1). UA or WS combined with YOH is a natural limitation for total amount of visitors served. A combination of UA or WS with YOH was considered to be the variable used for the regression analysis, but Visitors and WU seem to be more appropriate because of their higher correlations to DE (Table 1).

When deciding which of these two variables to include, the uncertainty connected to WU was taken into account. For most of the small and medium sized facilities it is difficult to obtain accurate measurements because they are often part of multi-purpose facilities and do not possess separate meters. Despite that, WU is highly dependent on the number of visitors as they trigger most of the water consumption in the facility. According to the authors' experience, bleed water and water for showers represents roughly equal water volumes. In theory, both water for showers and bleed water are highly dependent on the visitors. The bleed water need is based on the numbers of visitors but in most cases it is a fixed value based on an approximation of daily visitors. That explains also why WU shows a higher correlation coefficient to DE than Visitors (Table 1). Anyhow, because of the number of visitors being the main trigger for WU and DE and the uncertainty connected to WU, the authors included Visitors in the regression analysis.

Finally, the dependent variable in the presented multiple linear regression model is DE with Visitors, Age, AWT and HDD17 as independent variables. The regression model was then validated with an internal validation procedure. A data-splitting method was adopted, i.e. the original sample was randomly split in two samples: two thirds (67 datasets) were used to build the model and deviate the regression equation, the remaining third (33 datasets) was utilized to validate the model. The data-split percentage is within the range described by Harrell et al. [40].

Results and discussion

The following sections show the results and their discussion of the statistical analyses presented in the methodology section.

Assessment of the most common used EPIs

An objective of this publication was to examine if it makes a difference which EPI to use to express the energy performance of swimming facilities. EPIs typically adopted in literature to represent the energy performance of swimming facilities are DE normalized by UA and DE normalized by WS (see section 2). Starting from data stored in the database, those EPIs were calculated and are represented in Figure 3.

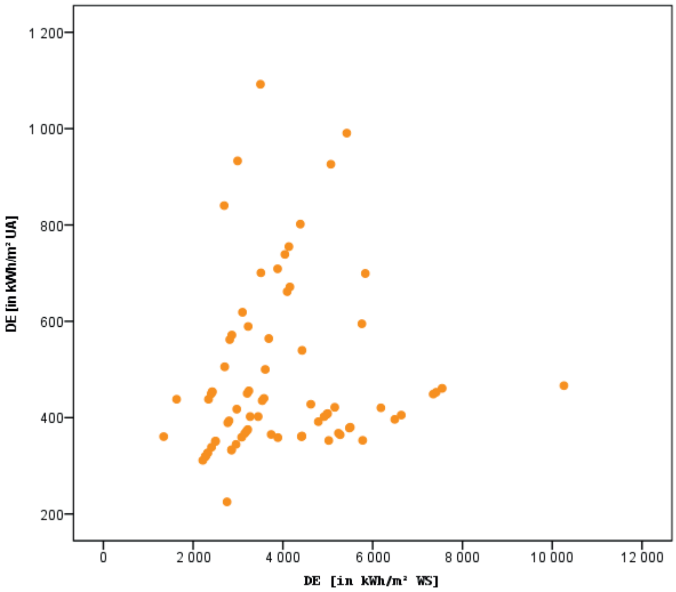
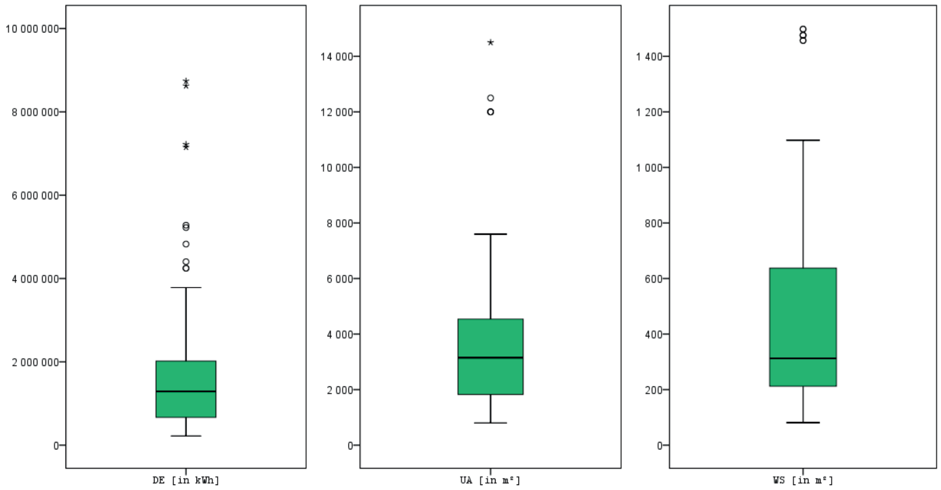


Figure 3: Representation of two EPIs: DE normalised by UA and DE normalized WS.

The figure shows a widely scattered distribution of data and confirms that the metric used to normalize the energy use actually influences the benchmark of a building. Some of the facilities showing low values when $\mathrm{kWh/m^2_{UA}}$ is used, exhibit high values when $\mathrm{kWh/m^2_{WS}}$ is applied and *vice versa*. Furthermore, Spearman's rank correlation coefficient showed a low ($\rho = 0.329$) and highly significant ($p \leq 0.01$) correlation between these two EPIs meaning that the two assessments are weakly represented by a monotonic behaviour. Therewith, the finding of Øen [26] that the choice of EPI is essential could be confirmed.

Univariate analysis

Figure 4 shows descriptive univariate statistics for all the variables of the swimming facilities included in this study. The bold line in the middle depicts the median, while the bottom of the green box represents the 1st quartile. The upper end of the green box shows the 3rd quartile. The whiskers represent the minimum and maximum values (without the outliers). SPSSs condition for outliers is if values excel 1.5 times interquartile range, which is defined as 3rd quartile minus the 1st quartile. Stars on the boxplot represent extreme values which are outliers but further off. The analyses described in the following chapters include the values marked as outliers by SPSS. They reflect the behaviour of existing swimming facilities and passed the authors quality control. E.g., the boxplot presenting `WS` in figure 4 shows three outliers which are far off. They represent the largest swimming facilities in Norway and are therefore included in the following analyses.



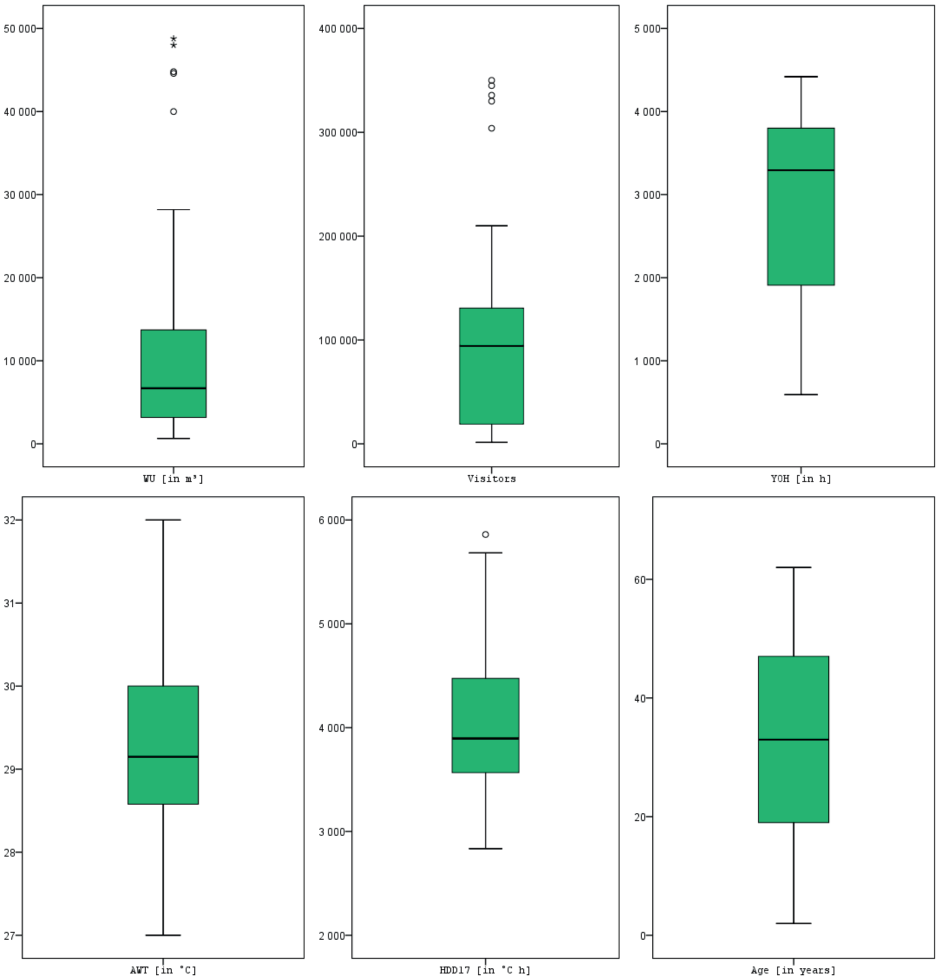


Figure 4: Boxplots of the investigated variables.

The Kolmogorov-Smirnov test confirmed that, with the exception of `AWT`, none of the variables are normally distributed. Likely because some variables are not random but are subject to some rules or constraints e.g., design recommendations, technical limits, and typical uses or habits.

Correlation analysis

After failing the Kolmogorov-Smirnov test for normality, a bivariate analysis was carried out to assess the mutual relationship between each variable stored in the database.

Spearman's rank coefficient was calculated for each couple of variables and the outcome of the bivariate analysis is reported in Table 1.

Table 1: Spearman's rank coefficient calculated for each couple of variables stored in the database.

	DD	**Age**	**UA**	**WS**	**WU**	**AWT**	**YOH**	**Visitors**
DE	-.280**	-.377**	.866**	.862**	.945**	.059	.595**	.894**
N	176	176	77	176	95	114	105	113
Visitors	-.294**	-.423**	.699**	.906**	.860**	.079	.643**	
N	113	113	41	113	76	100	68	
YOH	.124	-.822**	.550**	.838**	.481**	.116		
N	105	105	63	105	54	70		
AWT	-.146	-.122	-.829**	-.076	.129			
N	114	114	38	114	84			
WU	-.181	-.562**	.888**	.840**				
N	95	95	21	95				
WS	-.239**	-.578**	.827**					
N	176	176	77					
UA	-.454**	-.400**						
N	77	77						
Age	-.064							
N	176							

* significant at the 0.05 level

** significant at the 0.01 level

According to the correlation analysis (Table 1), `UA` and `WS` are, from a statistical point of view, equally well suited to be used as normalisation metric. However, the authors suggest to use `WS` as there is uncertainty bound to `UA`. Some facilities include the technical areas and some do not which will lead to a skewed analysis. Multi-purpose sports facilities (e.g., a combined swimming pool and sports hall) represent another challenge, as certain areas, such as changing rooms, the entrance area, showers etc., are shared and can lead to a biased analysis.

The highest correlation was found between `DE` and `WU` followed by `Visitors`, `UA` and `WS`. `DE` shows an equally high dependency of `UA` and `WS`. On the other side, `DE` is weakly correlated with climate ($\texttt{HDD}_{17}$) although statistically significant. The relationship between `DE` and average water temperature (`AWT`) does not achieve a statistical significant level ($p = 0.05$).

Multiple linear regression analysis

In order to perform a multiple linear regression analysis: (1) all variables had to be measured on a continuous scale, (2) the dependent variable needs be controlled for more than one independent variable, (3) independence of residuals has been proved with the Durbin-Watson statistic, (4) linearity shall be assumed between the dependent variable and each independent variable, (5) data have to show homoscedasticity, (6) the quality check on the database discarded those datasets with outliers, (7) the histogram of the residuals are approximately normal distributed, and (8) in order to avoid multicollinearity among `UA`, `WS`, `YOH`, `WU` and `Visitors`, a selection process (described in the method) was undertaken resulting in only `Visitors` being included in the regression model.

Moreover it was assumed that the buildings' age has a linear effect on the energy performance and all independent variables multiplied by appropriate unstandardized coefficients can be added. The multiple linear regression model is presented in table 2.

Table 2: Output from the regression analysis.

	Unstandardized coefficients		Standardized		
	B	Standard Error	Coefficients	t	Sig.
`Constant`	-1 493 586	1 880 057		-0.794	0.430
`Visitors`	14	1.1	0.847	12.492	0.000
$\mathtt{HDD}_{17}$	176	94	0.113	1.874	0.066
`Age`	-9 707	4 620	-0.137	-2.101	0.040
`AWT`	51 518	59 021	0.050	0.873	0.386

The result of the regression analysis (Table 2) shows that the variable `Visitors` is clearly the strongest trigger for `DE`. While $\mathtt{HDD}_{17}$, which represents the climate, has a minor but significant influence on `DE`, `AWT` has a very limited and non-significant impact. The results of the regression analysis are expressed through the following regression equation

$$\mathtt{DE} = 14\left(\frac{kWh}{visitor}\right)\cdot\mathtt{Visitors} + 176\left(\frac{kW}{°C}\right)\cdot\mathtt{HDD}_{17} \square 9\,707\left(\frac{kWh}{year}\right)\cdot\mathtt{Age} + 51\,518\left(\frac{kWh}{°C}\right)\cdot\mathtt{AWT} \square 1\,493\,586\left(kWh\right)$$

where `DE` is expressed in kWh. The result concerning the impact of the facilities' age on `DE` is interesting. There is a small and significant impact expressing that the lower the facilities' age the higher the `DE`. This finding is surprising as newer buildings are supposed to use less energy because of their expected superior building envelope and technology. An explanation can be that the newest facilities are mostly leisure pool facilities. They offer extensive services to their visitors, which increase their energy use.

Validation of the developed multiple linear regression model

As described in chapter 3.3.3, the approach chosen to validate the model was internal validation through data-splitting. After a completion check, 100 out the total 176 datasets provide data for all the variables used in the regression analysis. Two random samples have been created from the same underlying population of 100 datasets: 67 datasets serve for the development of the multiple linear regression and the remaining 33 datasets are used for model validation.

Figure 4 shows the outcome of the model validation represented in a scatterplot where the modelled DE values are on the x-axis and the measured DE values on the y-axis. Spearman's rank correlation coefficient is high ($\rho = 0.905$) and highly significant ($p = 0.000$), meaning that the two series are overall characterized by a slightly monotone behaviour. The coefficient of determination shows that the developed multiple linear regression model performs quite well in predicting the performance of Norwegian swimming facilities on the base of the independent variables ($R^2 = 0.743$), even if it is outside the scope of this paper.

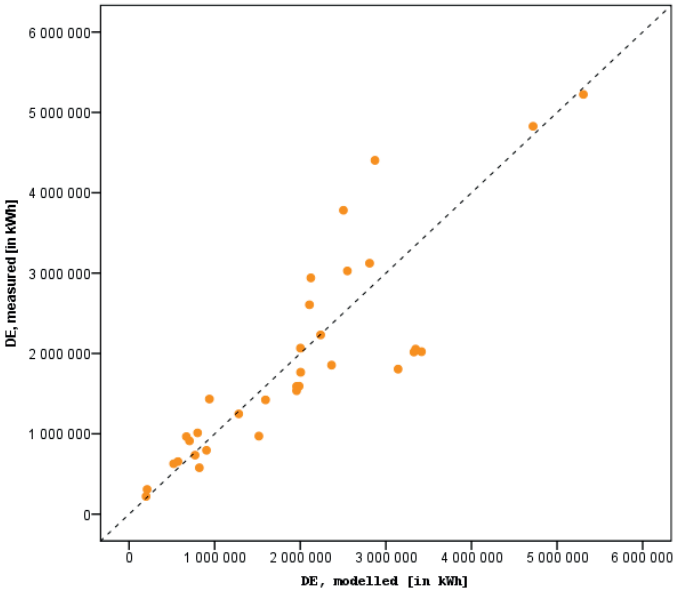


Figure 4: Scatter plot with the comparison of measured and modelled DE.

In general, deviations of predicted values from the observed values (called errors or residuals) are expected "to be (roughly) normal and (approximately) independently distributed with a mean of 0 and some constant variance" [41]. The residuals of the validation appear to behave randomly (Figure 5, left) and to be normal distributed (Figure 5, right); therefore, the developed model seems to fit the data quite well.

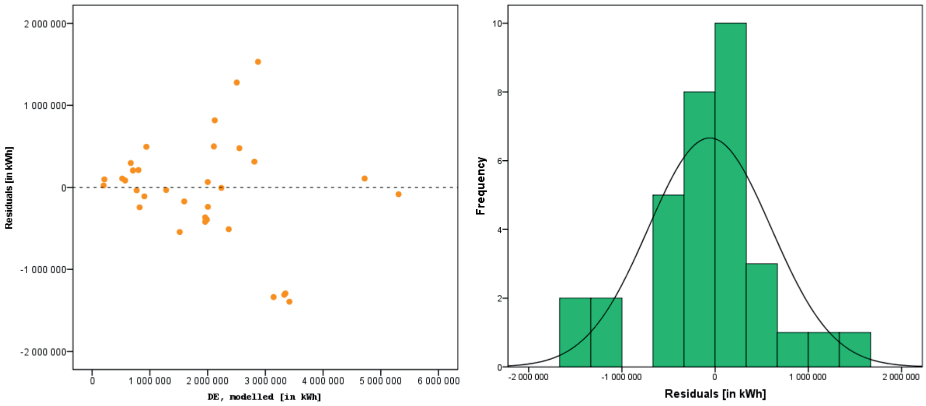


Figure 5: (left) Scatter plot with the comparison of residuals and modelled delivered energy (DE). (Right) Histogram of the residuals (normality).

Moreover, the residual statistics (MAPE, MAE, RMSE) quantify the magnitude of the deviations between the model-predicted and the collected values: the model-predicted performances differ (i) by an average of 24 % compared to the measured ones (MAPE = 23.683 %) and (ii) in absolute terms of about 450 MWh (MAE = 456 199 kWh), and (iii) the standard deviation of the residuals between predicted values and measured values is about 660 MWh (RMSE = 658 391 kWh), which is a measure of the accuracy of the model.

In summary, (i) the developed multiple linear regression model provides a reasonably good explanation of how much variance of the energy performance of Norwegian swimming facilities can be explained on the base of the used independent variable, and (ii) validation shows that the developed model estimates the energy performance of Norwegian swimming facilities with a quite good predictive accuracy on the base of the independent variable, even if the prediction aspects is outside the scope of this paper.

Conclusions

Swimming facilities can be described as process plants calling for specialized EPIs. This paper investigates the most used EPIs used in the literature and uses a correlation and multiple linear regression analysis to identify a reliable EPI for energy benchmarking. The analysis is based on 176 datasets which were collected with the help of the questionnaire. The main findings are:

- The choice of the EPI is important and the correlations between delivered energy (`DE`) and influencing factors show that the water usage (*`WU`*) and the number of visitors (`Visitors`) are the variables most strongly correlated to `DE`.

- If reliable data are available, the authors suggest to normalize DE with respect to the number of visitors (kWh/visitors) as a reliable and suitable EPI for swimming facilities. This is also in line with the paradigm of identifying swimming facilities as process plants where the process output is used as normalization metric [29, 30].

- However, it could be difficult to obtain consistent data for visitors for a large number of swimming pools. For these cases usable (floor) area (`UA`) or water surface (`WS`) could be used as normalisation metric as they are strongly and high significantly correlated to `DE`. Anyhow, the authors recommend to use WS as it is an explicit measurement that is easy to obtain with a high accuracy and precision, rather than UA which is bound to uncertainties. It is important to stress that, when using kWh/m^2_{WS} as EPI, only buildings offering (approximately) the same services to their visitors should be compared.

- The correct interpretation of the EPI is important as it only gives an overview and makes a comparison with other buildings possible. Underlying influencing factors which have to be considered are the building design and used equipment, the provided energy services and operation and maintenance [19].

References

[1] Department of Energy, 2010 Buildings energy data book, http://buildingsdatabook.eren.doe.gov/docs%5CDataBooks%5C2010_BEDB.pdf, (accessed 20.07.2015).

[2] Energy Information Administration, International Energy Outlook, 2013.

[3] Statens Energimyndighet, Energianvändning i idrottsanläggningar, 2009.

[4] ENOVA, Energibruk i ulike bygningstyper, http://www.enova.no/innsikt/rapporter/byggstatistikk-2011/4-energibruk-2011/43-energibruk-i-ulike-bygningstyper/43-energibruk-i-ulike-bygningstyper/490/1233/, (accessed 07.08.2015).

[5] T. Bøhlerengen, J. Mehus, A. Waldum, P. Blom, T. Farstad, Byggforsk håndbok 52: Bade og svømmeanlegg, Norges Byggforskningsinstitutt, Oslo, 2004.

[6] British Swimming, The Use of Energy In Swimming Pools, 2008.

[7] E. Trianti-Stourna, K. Spyropoulou, C. Theofylaktos, K. Droutsa, C.A. Balaras, M. Santamouris, D.N. Asimakopoulos, G. Lazaropoulou, N. Papanikolaou, Energy conservation strategies for sports centers: Part B. Swimming pools, Energy and Buildings, 27 (2) (1998) 123-35.

[8] H. Røkenes, Betraktninger rundt svømmehallers energieffektivitet [Master thesis], NTNU, 2011.

[9] W. Kampel, B. Aas, A. Bruland, Energy-use in Norwegian swimming halls, Energy and Buildings, 59 (0) (2013) 181-6.

[10] EN 15603:2008, Energy performance of buildings. Overall energy use and definition of energy ratings 2008.

[11] X. Xu, Model-based building performance evaluation and diagnosis [Dissertation], Hong Kong: The Hong Kong Polytechnic University, 2005.

[12] D. Claridge, C. Culp, S. Deng, W. Turner, J. Haberl, M. Liu, Campus-Wide Continuous Commissioning of University Buildings, In: Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, USA, 2000.

[13] S. Wang, C. Yan, F. Xiao, Quantitative energy performance assessment methods for existing buildings, Energy and Buildings, 55 (0) (2012) 873-88.

[14] N. Lior, Sustainable energy development: The present (2009) situation and possible paths to the future, Energy, 35 (10) (2010) 3976-94.

[15] European Parliament, Directive on the energy performance of buildings, France: European Parliament, 2002.

[16] European Parliament and Council, Energy performance of buildings, in: Directive 2010/31/EU, Official Journal of the European Union, Luxembourg, 2010.

[17] Concerted Action EPBD, Concerted action - energy performance of buildings, http://epbd-ca.eu (accessed 07.08.2015).

[18] D. Goldstein, C. Eley, A classification of building energy performance indices, Energy Efficiency, 7 (2) (2014) 353-75.

[19] D. Goldstein, J. Almaguer, Developing a Suite of Energy Performance Indicatiors (EnPIs) to Optimize Outcomes, In: Proceedings of the 2013 ACEEE Summer Study on Energy Efficiency in Industry, Washington, D.C., American Council for an Energy-Efficient Economy, 2013.

[20] A.I. Alkhamis, S.A. Sherif, Performance analysis of a solar-assisted swimming pool heating system, Energy, 17 (12) (1992) 1165-72.

[21] G.P. Greyvenstein, J.P. Meyer, The viability of heat pumps for the heating of swimming pools in South Africa, Energy, 16 (7) (1991) 1031-7.

[22] G.N. Tiwari, S.B. Sharma, Design parameters for indoor swimming-pool heating using solar energy, Energy, 16 (6) (1991) 971-5.

[23] A. Saari, T. Sekki, Energy Consumption of a Public Swimming Bath, The Open Construction and Building Technology Journal, 2 (0) (2008) 202 - 6.

[24] A.S. Abrahamsen, M. Bergh, N. Fedoryshyn, Statistics Norway - Energibruk i bygninger for tjenesteytende virksomhet 2011, 2013.

[25] W. Kampel, B. Aas, A. Bruland, Characteristics of energy-efficient swimming facilities – A case study, Energy, 75 (0) (2014) 508-12.

[26] M. Øen, Indoor Swimming Pools and Requirements for Energy Efficiency [Master Thesis], Trondheim: Norwegian University of Science and Technology, 2010.

[27] Teknologisk Institut, Nøgletal, energi- og vandforbrug i svømmehaller - Nøgletal fra 2006-2011, http://www.teknologisk.dk/ydelser/noegletal-energi-og-vandforbrug-i-svoemmehaller/noegletal-fra-2006-2011/21324, (accessed 07.08.2015).

[28] S.B. Shailendra Mudgal, Eric Hoa, Sarah Lockwood, Eric Labouze, Christine Pout, Roger Hitchin, Ralph Philip, Water Performance of Buildings, 2012.

[29] D. Saygin, E. Worrell, M.K. Patel, D.J. Gielen, Benchmarking the energy use of energy-intensive industries in industrialized and in developing countries, Energy, 36 (11) (2011) 6661-73.

[30] L. Pérez-Lombard, J. Ortiz, R. González, I.R. Maestre, A review of benchmarking, rating and labelling concepts within the framework of building energy certification schemes, Energy and Buildings, 41 (3) (2009) 272-8.

[31] International Organization for Standardization, ISO/TR 16344:2012: Energy performance of buildings - Common terms, definitions and symbols for the overall energy performance rating and certification, 2012.

[32] P. Torcellini, S. Pless, M. Deru, D. Crawley, Zero Energy Buildings: A Critical Look at the Definition, in: ACEEE Summer Study, Pacific Grove, California, USA, 2006.

[33] International Organization for Standardization, ISO 9836:2011: Performance standards in building - definition and calculation of area and space indicators, 2011.

[34] Meteo Norge, Kommentarer til beregning av energi gradtall 2014 (Comments on the calculation of the degree-days of 2014), 2015.

[35] Ministry of Culture, Statusrapportering for svømmebasseng - 2012, Oslo: 2013.

[36] Laerd Statistics, Pearson Product-Moment Correlation, https://statistics.laerd.com/statistical-guides/pearson-correlation-coefficient-statistical-guide.php, (accessed 20.07.2015).

[37] B. Rosner, Fundamentals of Biostatistics, 7th Edition, Cengage Learning, Boston, 2010.

[38] C.J. Kowalski, On the Effects of Non-Normality on the Distribution of the Sample Product-Moment Correlation Coefficient, Journal of the Royal Statistical Society, 21 (1) (1972) 1 - 12.

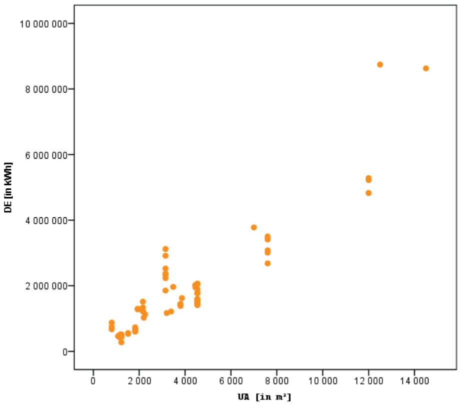
[39] J. Hauke, Kossowski, T., Comparison of values of Pearson's and Spearman's correlation coefficients on the same sets of data, Questiones Geographicae, 30 (2) (2011) 87 - 93.

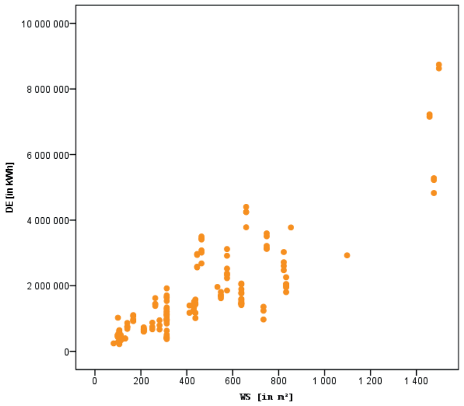
[40] F.J. Harrell, K. Lee, D. Mark, Multivariableprognostic models: issues in developing models, evaluating assumptions and adequacy, and measuring and reducing errors, Statistics in medicine, 15 (1996) 361 - 87.

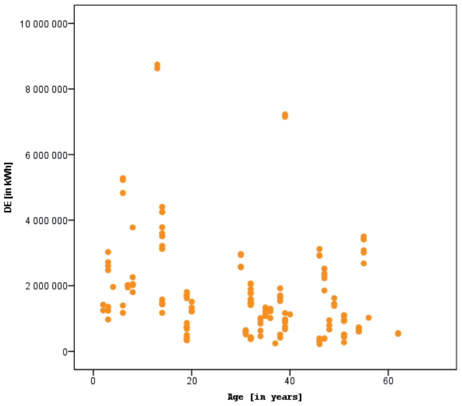
[41] NIST/SEMATECH, e-Handbook of Statistical Methods, in: Engineering Statistics Handbook, NIST/SEMATECH, 2012.

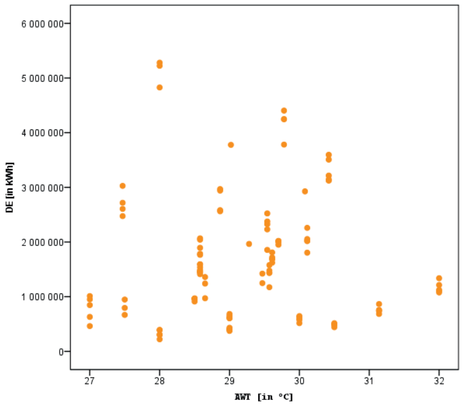
Appendix

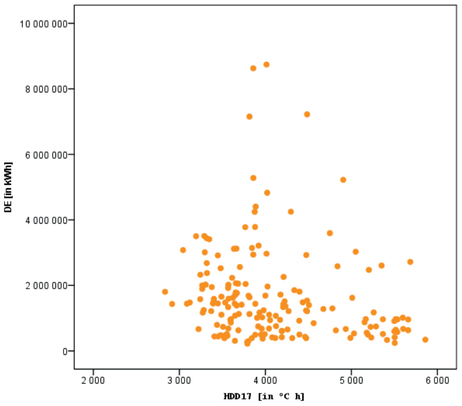
The scatter plots for DE and the variables of interest provide a better overview of the data distribution as Spearman's correlation coefficient is a rank-based correlation.

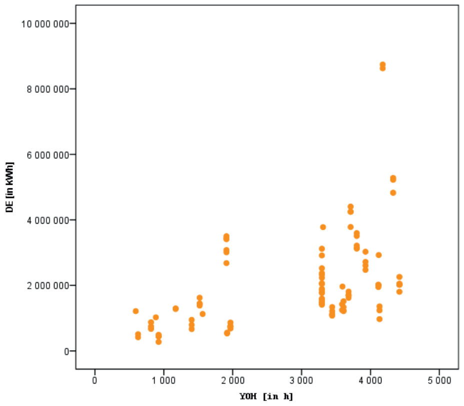












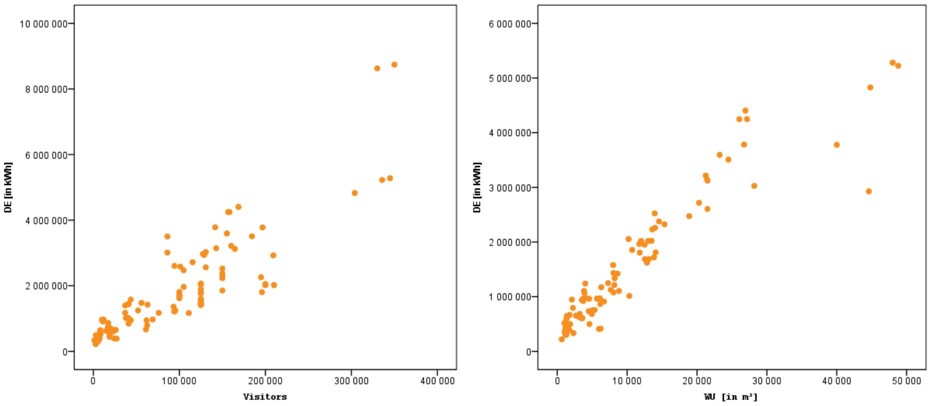


Figure A.1. Scatter plots for DE and the variables of interest

Paper III

Kampel, W., Aas, B. and Bruland, A., Characteristics of energy-efficient swimming facilities – a case study. Energy, 75 (2014), p 508 – 512.

DOI: 10.1016/j.energy.2014.08.007

Characteristics of energy-efficient swimming facilities – a case study

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Abstract

The European Union has introduced a directive with the aim to reduce primary energy production. With 40 % of energy consumption connected to buildings there is a particular need of understanding the energy consumption profile and determine measures to achieve the agreed targets. Swimming facilities is a building category with particularly high energy consumption. The aim of this paper is to identify energy-efficient facilities and do an in-depth analysis to be able to determine their characteristics and further to describe how they achieve this low energy consumption. In order to find the most energy-efficient facilities, questionnaires were sent to all Norwegian swimming facilities. The results were screened and a follow up questionnaire, making a deeper analysis possible, was sent to the facilities with the lowest energy-use. The in depth analysis showed that the facilities with the lowest energy consumption use heat exchangers and heat pumps to recover energy from the outgoing water and air. The energy is then used to warm up incoming air, pool water and tap water. However, it can be seen that even the best swimming facilities have room for improvement.

Introduction

In Europe, there is an overall target of energy savings in primary energy production of 20% within 2020 [1]. Around 40% of energy consumption is related to buildings [2] and there is a considerable need of action in order to reach the mentioned targets. Within the building sector, sports facilities may be described as high-level energy consumers [3], where swimming pools and ice rinks are on top [4]. This paper describes a case study on Norwegian swimming pools.

In order to meet the requirements of different user groups there is a considerable variety of swimming facilities in Norway. While a little shallow pool is enough for pupils to learn swimming, the features of the largest facilities (leisure pool facilities) are completely different. Their offer often includes a pool of international size, a pool with artificial waves, a diving platform, different water attractions and relaxation areas like a restaurant, spa or sauna. Opening hours reflect the variety of size where small school pools are open for 20 hours per week and the largest facilities for up to 80-90 hours per week for.

These different concepts result in different building envelopes, HVAC systems and water treatment systems [5] which is expected to lead to equal variation in energy use. Some data about energy use in swimming facilities are published [4-10] but little is stated on why facilities achieve low energy consumption. Further, several papers deal with specific subjects related to the water and energy aspects of swimming facilities, like evaporation [11-13], heat pumps [14-18] and building envelope [19].

The publications about evaporation from Shah [11, 13] focus almost exclusively on the calculation while Asdrubali [12] included a chapter about energy consumption. However, no solutions or suggestions are given.

The publications concerning heat pumps [14-18] conclude that this investment leads to savings in energy consumption. Sun et al [16] calculated the payback period to be 1.1 year for a pool in Shanghai when investing in using a ventilation system with a heat pump dehumidifier. Additionally, it must be mentioned that investment in energy saving measures is closely related to the price structure for energy in each country, in particular price differences in electric and thermal energy [20].

Trianti-Stourna et al. [5] state that the energy-use for swimming facilities in Mediterranean climate is about 4300 kWh/m² water surface (WS) and up to 5200 kWh/m²

WS for buildings in the continental European zone. There is no indication about where these numbers originate from. The authors suggest architectural and electromechanical interventions to improve the energy-efficiency of swimming facilities.

A Finnish publication [6] deals with one swimming facility in Finland calculating the energy use to be 2784 kWh/m² WS per year. This number is much lower than the one presented by Trianti-Stourna et al. [5] but it represents only one swimming facility on a theoretical basis.

Data from Germany [7] and Norway [8] include swimming facilities from the whole country and show a large spread in energy use. The papers include only statistics and no more information about what makes the difference between swimming facilities with high and low energy consumption.

In a publication by Swedish public authorities [4] the numbers are presented in kWh/m² useable area (UA) and it is not stated from where these numbers originate. The only known fact is that no multi-purpose facilities are included. The publication reports the distribution of energy to the different subsystems but there is no distinction between the swimming facilities with high and low energy consumption.

British authorities [9] distinguish between "typical practice" and "good practice" without defining criteria for the categories.

The study published by Kampel et al [8] divides the facilities in groups based on their WS and analysed their final annual energy consumption (FAEC). Considerable variations were found within the groups leading to the research question for this paper. How can the most energy-efficient swimming facilities be described? What makes the difference between facilities with high and low energy consumption?

Methods

A questionnaire was used to collect data from Norwegian swimming facilities. In total, more than 250 datasets (one dataset is defined as the FAEC for one year for one swimming facility) were collected where a bit more than a third (37%) could not be used due to inaccuracy, missing data or the lack of energy measuring devices at the facilities. The questionnaire was processed by senior staff at the facilities.

The swimming facilities were divided into three categories. The buildings in category one are characterized by containing one pool. The second category includes facilities with two or three pools. Typically, a sports pool and a therapy pool that is slightly warmer. The third category consists of the biggest swimming facilities with several pools and water attractions. These categories differ slightly from the ones used by Kampel et al [21] and the Danish Technological Institute [10]. The central change is the shift of facilities with a sports pool of 25 m x 12.5 m (WS of 312.5 m^2) from the second to the first category.

The term WS used in the article is equal to the pool surface area. The attractions are not included, but an overview can be found in table 2.

The facilities were evaluated concerning their energy consumption and a follow up questionnaire was sent to those using the lowest amount of energy in each category to learn more about their characteristics. As benchmark for energy consumption kWh/m^2 WS/opening hour was used as suggested by Kampel et al. [21]. In the analysis, delivered energy [22] is studied while primary energy is not discussed. The whole questionnaire with all included questions can be found in the Appendix. Further information was collected by personal communication with plant representatives.

The original intention was to investigate three pools in each category, which was not possible under the given circumstances. The authors met the greatest challenges concerning swimming facilities in category one as this building type is often combined with other sports halls or facilities and have no separate measuring devices installed. In general, some of the swimming facilities, which seemed to show good energy performance, turned out to be not so energy-efficient after a deeper analysis, and had to be excluded. Another reason to exclude answers was a general lack of understanding of the energy systems by plant operators, leading to inaccurate responses.

Climate correction was applied, as the FAEC of the different swimming facilities is dependent on the location and annual climate variations. Referring to Enova [23], 40% of the FAEC in swimming facilities are influenced by the climate and needs to be adjusted. All data was corrected, using the Oslo climate of 2010 (degree-days of Oslo in 2010) as reference, with the following formula [24]:

$$FAEC_{Oslo} = FAEC_{actual\ facility}\left((1-0.4) + 0.4 * \left(\frac{Degreedays_{Oslo}}{Degreedays_{actual\ facility}}\right)\right)$$

The Norwegian degree-days for the calculations originate from Enova's website [25] and where recalculated to fit with the actual opening period of the facilities during the year.

Error analysis

The authors are dependent on the quality of the reported data and therewith on the staff in the different swimming facilities. Quality control was applied but is only applicable to a certain degree and cannot eliminate the uncertainties completely.

The degree-day method is an acknowledged procedure [26] and widely used by EU member countries [27]. Enova [23] suggests to apply climate correction to 40% of FAEC which is based on experience. This percentage is hard to verify as it is expected to vary between different facilities. Variations in the age of the facilities, energy management and usage patterns may change the climate dependent share.

Results

Table 1: Overview over the collected data for all swimming facilities.

	Category 1		Category 2		Category 3	
	Facility 1	**Facility 2**	**Facility 3**	**Facility 4**	**Facility 5**	**Facility 6**
Building year	1966	1969	1995	1982	2008	2007
Annual opening hours	1 404	2 904	3 682	3 294	4 328	4 114
Annual visitors	55 000	44 700	100 000	130 000	365 000	210 000
Air temperature [C°]	30	32	28	30 - 33	31	31
Water temperature [C°]	27.5	28 - 32	28.5	29.6	28	28.9
Humidity [%]	55	55	55	55	55 - 60	60
WS [m²]	281	312.5	548.5	637.5	1 467	1 170
Water consumption [m³]	3 563	6 500	13 278	11 817	48 418	16 250
Water consumption per person [l]	65	145	133	91	133	77
FAEC [kWh/m² WS/hour opened]	2.93	1.40	0.86	0.78	0.89	0.47
Automatic water quality control	✓	✓	✓	✓	✓	✓
Water quality within regulations	✓	✓	✓	✓	✓	✓
Heat pump for filter cleansing (pool refill)				✓		✓
Heat exchanger for grey water (showers)	✓		✓			
Heat pump for grey water (showers)				✓	✓	✓
Heat exchanger in HVAC	✓					
Heat pump in HVAC		✓	✓	✓	✓	✓
Energy from HVAC distributed to air	✓	✓	✓	✓	✓	✓
Energy from HVAC distributed to pool water		✓	✓	✓	✓	✓
Energy from HVAC distributed to tap water		✓		✓		✓

All facilities fulfill the requirements concerning water quality. Chlorine is used for disinfection and all facilities use pressurized sand filters. Additionally, some use an activated carbon filter in partial flow and UV equipment for disinfection. Facilities 1, 2 and 4 are closed during the summer (school holidays) while the other facilities are open during the whole year.

With respect to filter cleansing, different concepts are identified. Filter backwash may be manual or automatic. The cleansing procedure varies from all filters being backwashed during the opening hours to automatic backwash of filters during nighttime.

The facilities in category 1 are older than 40 years but only facility 2 went through major refurbishment in 2003 (ventilation and water treatment) and 2009 (renovated poolroom and improved insulation of the outer walls). Facility 4 and 6 had minor renovation of the building (civil works) while facility 3 and 5 are unchanged since they were built.

In addition, table 1 shows a relationship between the used technology for water and energy management and the FAEC. Facilities equipped with the whole range of systems for energy recovery are the ones with the lowest FAEC. Table 1 shows that the selection and configuration of technology has a strong impact on annual water and energy consumption. The technologies described include products from European suppliers and are commonly used in Norwegian swimming facilities.

Table 2: Water attractions in different facilities

Category 1		Category 2		Category 3	
Facility 1	**Facility 2**	**Facility 3**	**Facility 4**	**Facility 5**	**Facility 6**
small children slide				small children slide	
	1m springboard				
		slide (55m)	slide (42m)	2 slides (63 m & 67 m)	2 slides (60m)
		divng plattform	diving plattform	diving plattform	diving plattform
			whirlpool	whirlpool	whirlpool
			sprays	sprays	sprays
			flow channel	flow channel	flow channel
			steam bath	steam bath	steam bath
		sauna	sauna	sauna	sauna
		solarium	solarium	solarium	solarium
					counter current system

The categories show a significant spread concerning water attractions (Table) with facilities 1 and 2 offering few attractions while facilities 4, 5 and 6 provide a wide variety of features. The item "sprays" includes attractions like water mushrooms, waterfalls, fountains, water cannons, etc. The heat loss due to evaporation increases energy consumption but most of it can be recovered by modern technology. The bigger contributor to FAEC is electricity, which is needed for the rotating equipment to operate the attractions

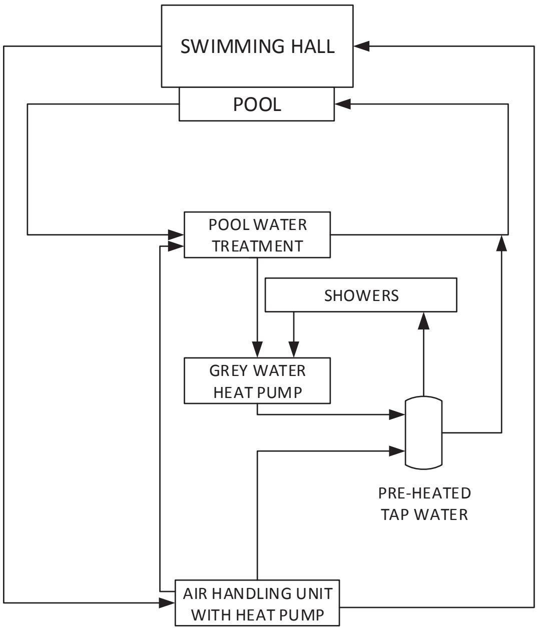

Figure 1: Energy flux for the swimming facilities the most advanced technology (facilities 4 & 6).

The flow chart in figure 1 shows the energy flux in a plant using the most advanced concepts for energy recovery (facility 4 and 6). The flow chart illustrates a short loop (pool water) and a long loop (poolroom ventilation). Both pool water, tap water and air are energy carriers. The flow chart shows only the energy flux inside the building.

The embedded heat pump in the air-handling unit recovers energy from exhaust air from poolroom, and delivers energy for preheating of incoming air, pool water and tap water. The grey water heat pump collects energy in grey water from showers and filter cleansing. The warm side of the heat pump delivers energy to tap water, used for refilling pools, or further heated for use in showers.

Discussion

Table 1 shows that even some of the most energy-efficient swimming facilities in Norway differ significantly considering their performance data. The significant difference between the studied facilities in category 1 has different reasons. Both facilities are approximately equally old but facility one did not have any refurbishments. Besides that, facility 2 has a modern HVAC system but does not recover any energy from wastewater. Another interesting aspect is water consumption, especially proportional to visitors. The substantial variation of water consumption can be explained by the showers, where 9.75 litres per minute (l/min) pass through the shower heads in facility 1 compared to 15 l/min in facility 2. Another influencing factor is the grey water management. Facility 1 achieves good water quality when exchanging only the water from filter cleansing. In facility 2 an additional 4 m^3 water per day have to be exchanged in order to achieve good water quality.

The difference in energy consumption of the two facilities in category 2 is approximately 10 %. Facility 4 uses significantly less water per person than facility 3 which can be partly explained by the showerheads (10 l/min versus 9 l/min). Concerning energy consumption facility 4 uses more advanced technology recovering energy from the wastewater of the showers and the HVAC system recovers excess energy also for preheating of tap water.

The buildings included in category 3 show a substantial difference in FAEC, Facility 5 uses almost the double amount of energy as facility 6. The reasons are a more advanced HVAC system in facility 6, which recovers energy also to tap water, and energy recovery from the backwash of filter cleansing. Facility 5 has a considerable higher water consumption compared with facility 6. This may partly be described by shower properties (10 l/min vs 6 l/min flow rate) and partly by the extra feeding of bleed water (4.4 m^3/day) in order to maintain water quality within limits. Further, the filter configuration in facility 5 with horizontal sand filters requires more frequent backwash, increasing water consumption.

In general, the flow rates of the used shower heads needs to be discussed as water for the showers represents a big share of the total water consumption. While the flow rate is easy to measure the behaviour of the visitors is uncertain. It is unclear if all of the visitors take a shower before and after entering the pool and for how long they use the showers. An average value for the shower duration based on experience is 7 minutes [28].

Another interesting observation is that facilities 2 and 5 use horizontal sand filters, which are known to be designed with lower surface load and more frequent backwashing. Still the plants report a need of additional feeding of tap water to the pools for keeping the water quality within the regulations.

The total energy demand is mostly dependant on the used technology for energy and water management, with the building envelope being not as important [29]. Kampel et al. [21] showed that FAEC, amongst others, is highly dependent on water consumption. This finding could be confirmed for the facilities in categories 2 and 3 meaning that an energy analysis always has to include an equal analysis of water balance.

The facilities redirecting recovered energy from the ventilation system to pool and tap water show a better energy performance (FAEC). Especially in the summer months, there is a substantial surplus of energy in the air from the swimming hall [16, 29] and it is important that this surplus is not wasted. Sun et al [16] show in their case study from Shanghai that the recuperated energy from the ventilation is enough to heat pool water for more than eight months per year. Facility 1 has a significant unused potential, as they do not distribute the recovered energy from the air to pool and tap water. Facilities 3 and 5 have an unused capacity too, as they do not recover energy to the tap water.

A possibility to use the energy surplus [16, 29] is combining water and energy systems by using holding tanks for grey water and pre-heated tap water. Two storage systems are necessary for the system to work. The heat pump recovering energy from grey water has to be operational as long as possible. Therefore, the storage tank is needed to store energy in form of grey water and make it available for the heat pump to use. Typically, the storage tank is filled with grey water caused by the visitors during the day. Flushing the filters during the night makes it possible for the heat pump to run around the clock. Further, it is important to transfer the recuperated energy to a new medium to make it available when needed. A logic choice for swimming facilities is to save pre-heated water in storage tanks. As tap water is mainly used for showers and refilling pools after backwash, refilling should only be done during night time to reduce the need of storage volumes.

An interesting observation is that the used technology is not new and most of it is described in the literature. Water-water heat recovery in swimming facilities is well described in the paper from Chan & Lam [14]. Energy recovery from air to air has been known since the 1960s. During the last decades this technology has been improved. Sun et al [16] and Johansson & Westerlund [15] describe a HVAC system where energy is recovered from exhaust air and applied to incoming air and pool water. The most advanced solutions identified in this study show a slightly more sophisticated system. To the knowledge of the authors, this system is not described in the literature yet. The recovered energy is used to heat the incoming air, pool water and tap water. For this solution to work, it is essential that the condensers for air and pool water are arranged parallel and not in series. After the condensers, an aftercooler for preheating of tap water is essential to achieve the best result.

Conclusion

Good energy management in swimming pools requires recovery of energy from air and water and distribution of recovered energy to air and water, features that were found in all investigated facilities. The ones using the most advanced technology used least energy. The relationship between water and energy consumption was found to be inconsistent. Low water consumption does not necessarily result in a low FAEC but the two facilities with lowest FAEC use very little water, too. Partly explanations for the significant differences in water consumption are the flow rates of the shower heads and the use of bleed water to keep water quality within regulations. However, these two factors do not account for all of the differences found, leaving some of the triggers for low water consumption unexplained. With Norwegian climate and energy prices, energy recovery is best achieved using heat pumps. The most efficient swimming facilities have established storage volumes for grey water as well as preheated tap water to maximize the heat pump's operation time. It is essential that HVAC systems are designed to recover energy from air and distribute it to the incoming air, pool water and tap water.

Most of the facilities among the best in Norway in terms of energy management show potential for improvement.

Appendix A

The questionnaire used for in depth analysis of the selected swimming facilities.

Questionnaire swimming hall

Facility name: Click here to enter text.
Contact person (Name and phone): Click here to enter text.

Total annual energy consumption				
2008	**2009**	**2010**	**2011**	**2012**
Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.

Building year: Click here to enter text.
Rehabilitation (when & what): Click here to enter text.

Weekly opening hours Click here to enter text.

Closed periods Click here to enter text.

Number of employees (what kind of employment?) Click here to enter text.

Yearly visitors Click here to enter text.
School (if available) Click here to enter text.
Rental (if available) Click here to enter text.
Paying audience (if available) Click here to enter text.
Others (if available) Click here to enter text.

Building envelope:
U-values: Click here to enter text.
Walls Click here to enter text.
Roof Click here to enter text.
Floor Click here to enter text.
Window area in % of facade Click here to enter text.

Air temperature Click here to enter text.

Relative humidity: Click here to enter text.

Chlorine or chlorine free? Click here to enter text.

Is water quality within regulations? Yes ☐
No ☐

Is water quality steered automatically? Yes ☐ No ☐

Amount of water circulation (normal operation and maximum): Specify if several circuits exist and which pools are connected to which circuit
Click here to enter text.

Heat exchanger for pool water? Yes ☐ No ☐

Heat pump for grey water? Yes ☐ No ☐

Preheating of water before it enters the system? Yes ☐ No ☐

Pools (for example: sports pool, therapy pool, whirlpool, etc)

Pool (sports pool, therapy pool, wave pool, etc)	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.
Size (length, width, depth)	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.
Water temperature	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.

Annual water consumption				
2008	**2009**	**2010**	**2011**	**2012**
Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.	Click here to enter text.

Attractions

Slide	Yes ☐ No ☐
Diving platform	Yes ☐ No ☐
Whirlpool	Yes ☐ No ☐
Others	Click here to enter text.

Filters

Type and amount Click here to enter text.
Capacity Click here to enter text.
Automatic or manual flushing? When? Click here to enter text.
What happens to the water from filter cleansing? Is it directed directly to the sewer or via a heat recovery system? Click here to enter text.

Lighting:
Which bulbs are used? Click here to enter text.
Movement sensors? Where? Click here to enter text.

HVAC
Brand/productClick here to enter text.
Airflow per day/week/monthClick here to enter text.
Amount of fresh air? As required? A certain percentage? Click here to enter text.
Heat pump? Yes ☐ No ☐
Product? Click here to enter text.
Energy recovered to air? Yes ☐ No ☐
Product? Click here to enter text.
to pool water? Yes ☐ No ☐
Product? Click here to enter text.
to water for showers? Yes ☐ No ☐
Product? Click here to enter text.

Comments
Click here to enter text.

References

[1] European Commission, The EU climate and energy package, http://ec.europa.eu/clima/policies/brief/eu/index_en.htm, (accessed 08.04.2014).

[2] International Energy Agency, Energy efficiency, http://www.iea.org/aboutus/faqs/energyefficiency/, (accessed 08.04.2014).

[3] ENOVA, Energibruk i ulike bygningstyper, http://www.enova.no/innsikt/rapporter/byggstatistikk-2011/4-energibruk-2011/43-energibruk-i-ulike-bygningstyper/43-energibruk-i-ulike-bygningstyper/490/1233/, (accessed 17.06.2014).

[4] Statens Energimyndighet, Energianvändning i idrottsanläggningar, http://www.orsa.se/wk_custom/documents/%7B8a31df1e-7390-4221-8e5c-5a91111706dd%7D_energi_i_idrottsanlaggningar.pdf, (accessed 17.06.2014).

[5] E. Trianti-Stourna, K. Spyropoulou, C. Theofylaktos, K. Droutsa, C.A. Balaras, M. Santamouris, D.N. Asimakopoulos, G. Lazaropoulou, N. Papanikolaou, Energy conservation strategies for sports centers: Part B. Swimming pools, Energy and Buildings, 27 (2) (1998) 123-135.

[6] A. Saari, T. Sekki, Energy Consumption of a Public Swimming Bath, The Open Construction and Building Technology Journal, 2 (0) (2008) 202 - 206.

[7] Deutsche Gesellschaft für das Badewesen e.V., ÜÖBV-Report, Essen, 2012.

[8] W. Kampel, B. Aas, A. Bruland, Energy-use in Norwegian swimming halls, Energy and Buildings, 59 (0) (2013) 181-186.

[9] British Swimming, The Use of Energy In Swimming Pools, http://www.swimming.org/assets/uploads/library/Use_of_Energy_in_Pools.pdf, (accessed 17.06.2014).

[10] Teknologisk Institut, Nøgletal, energi- og vandforbrug i svømmehaller - Nøgletal fra 2006-2011, http://www.teknologisk.dk/ydelser/noegletal-energi-og-vandforbrug-i-svoemmehaller/noegletal-fra-2006-2011/21324, (accessed 17.06.2014).

[11] M.M. Shah, Prediction of evaporation from occupied indoor swimming pools, Energy and Buildings, 35 (7) (2003) 707-713.

[12] F. Asdrubali, A scale model to evaluate water evaporation from indoor swimming pools, Energy and Buildings, 41 (3) (2009) 311-319.

[13] M.M. Shah, Improved method for calculating evaporation from indoor water pools, Energy and Buildings, 49 (0) (2012) 306-309.

[14] W.W. Chan, J.C. Lam, Energy-saving supporting tourism sustainability: A case study of hotel swimming pool heat pump, Journal of Sustainable Tourism, 11 (1) (2003) 74-83.

[15] L. Johansson, L. Westerlund, Energy savings in indoor swimming-pools: comparison between different heat-recovery systems, Applied Energy, 70 (4) (2001) 281-303.

[16] P. Sun, J.Y. Wu, R.Z. Wang, Y.X. Xu, Analysis of indoor environmental conditions and heat pump energy supply systems in indoor swimming pools, Energy and Buildings, 43 (5) (2011) 1071-1080.

[17] L. Westerlund, J. Dahl, Use of an open absorption heat-pump for energy conservation in a public swimming-pool, Applied Energy, 49 (3) (1994) 275-300.

[18] L. Westerlund, J. Dahl, L. Johansson, A theoretical investigation of the heat demand for public baths, Energy, 21 (7–8) (1996) 731-737.

[19] P.R.D. Isaac, C.R. Hayes, R.K. Akers, Optimisation of water and energy use at the Wales National Pool, Water and Environment Journal, 24 (1) (2010) 39-48.

[20] Eurostat, Energy price statistics, http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Energy_price_statistics, (accessed 08.04.2014).

[21] W. Kampel, B. Aas, A. Bruland, Energy Performance Indicators for Swimming Facilities, to be published.

[22] EN 15217:2007, Energy performance of buildings—methods for expressing energy performance and for energy certification of buildings, 2007

[23] ENOVA, Enovas byggstatistikk 2010, http://www2.enova.no/publikasjonsoversikt/file.axd?ID=594&rand=33fc85df-11da-4041-8d7c-e530c6104371 (accessed 17.06.2014).

[24] ENOVA, Enovas byggstatistikk 2008, http://www2.enova.no/publikasjonsoversikt/file.axd?ID=511&rand=7317f062-e3c9-4125-b3b8-657e879b4ad9, (accessed 07.07.2014).

[25] ENOVA, Graddagstall, http://www.enova.no/radgivning/naring/praktiske-ressurser/bygningsnettverket/graddagstall/290/0 (accessed 17.06.2014).

[26] Pöyry Management Consulting AS, Evaluering av modeller for klimajustering av energibruk, http://webby.nve.no/publikasjoner/rapport/2014/rapport2014_07.pdf, (accessed 17.06.2014).

[27] European Union, Implementing the Energy Performance of Buildings Directive (EPBD), 2010.

[28] A.M. Thomassen, Utbedring av svømmehall [Master thesis], NTNU, 2013.

[29] H. Røkenes, Betraktninger rundt svømmehallers energieffektivitet [Master thesis], NTNU, 2011.