Master Thesis – Master Energy Science

Non-Energy Benefits Brought by the Use of Variable Frequency Drives in Pump and Fan Applications

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Abstract

Energy efficiency is one of the most cost-effective ways to enhance security of energy supply, to boost businesses' competitiveness and to reduce the environmental burden of the energy system. Despite of its relevance, an energy efficiency gap has been identified in the industry. Highlighting non-energy benefits (NEB's) appears to be an effective approach to curtail this gap and attract the attention of firms. NEB's can overcome barriers to implement energy efficiency measures by relating them to the core business and competitive advantage of a company.

Special attention must be given to the industry sector due to its large energy requirements. Fixed-speed electric motors represent the main electricity users at industries. About two-thirds of the motors drive pump and fan applications which do not need constant motor speeds. For this reason, a great potential of energy benefits (EB's) can be derived from implementing Variable Frequency Drives (VFD's). VFD's are electronic controllers that vary the speed of the motors to meet specific load demands. This thesis investigates the NEB's and the profitability potential that VFD's can bring in pump and fan applications at the industry sector by following a three-phase method.

First, the benefits are identified and validated through surveys conducted to professionals in the field of VFD's. A descriptive list including the specific NEB's, their citation number in the included literature and their contribution to competitive advantage concept resulted from this phase. This list showed that "Improved process control", "Improved quality", "Decreased noise", "Reduced tear and wear on equipment machinery" and "Reduced emissions" and the categories "Operation and Maintenance" and "Production" are the most frequently cited NEB's in both scientific and manufacturers literature.

Next, the extent to which the NEB's can be quantified is evaluated. Two NEB's, "Reduced GHG emissions" and "Extended lifetime of equipment" resulted to be quantifiable and applicable to all pump and fan installations as an ex-ante evaluation. A theoretical study case is thereafter presented to show how the quantification of these benefits can increase the profitability of an energy efficiency investment. This evaluation is made by comparing the payback period (PBP), net present value (NPV) and internal rate of return (IRR) indicators to the values obtained from only accounting the EB's. Results showed that the economic benefits of the ex-ante NEB's assessed are greater in countries with the combination of lowest electricity prices and highest CO_2 emission factors, in processes with slightly reduced speed requirements and in larger motors power ratings with insulation classes A or B.

Finally, the calculation method used to assess the benefits is structured and described. A spreadsheet-based model compiling this calculation method is developed as an outcome of this research. It quantifies the EB's and NEB's applicable to all pump and fan installations. This model provides a transparent method for quantifying benefits and works as an ex-ante tool to assess VFD's energy efficiency projects at firms.

Although the quantification and profitability potential of NEB's as an ex-ante is limited as it depends on a number of variables, or events unable to predict, the qualitative findings of this research provide favourable arguments for the implementation of VFD's in the industry sector. Moreover, by highlighting the advantages of VFD's, this thesis aims to increase the awareness of governments and standardization bodies to develop missing standards and regulation policies regarding electric motor drive systems.

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List of Nomenclature

Greek letters

$\overline{\omega}$	Speed ratio
$\propto$	Capital recovery factor
ρ	Density of the fluid (kg/m^3)
α	Load ratio
η_f	Fan efficiency
η_m	Efficiency of the motor
η_p	Pump efficiency
$\eta_{p/f}$	Efficiency of the pump or fan
ΔP	Pressure differential (Pa)
ΔT	Allowable temperature rise (°C)
η_{VFD}	Efficiency of the VFD

Roman letters

$\#m_{repl}$	Number of motor replacements required
a	Maximum head
b	Coefficient characteristic of the pump or fan curve
B	Annual benefits (€)
c	Coefficient characteristic of the pump or fan curve
C	Annual costs (€)
$C_{CO2,allow}$	Cost of CO_2 emission allowances (€)
$C_{CO2,sav,yr}$	CO_2 cost savings per year (€)
C_{elec}	Electricity price (€)
$C_{Esav,yr}$	Electricity cost savings per year (€)
C_{motor}	Cost of the motor (€)
$C_{motsav,yr}$	Avoided capital loss per year due to extended lifetime of the motor (€)
$CO_{2,sav,yr}$	CO_2 emission savings per year (tonnes)
$E_{sav,yr}$	Energy savings per year (kWh, MWh)
$E_{throttle,yr}$	Energy consumption per year, throttle control method (kWh, MWh)
$E_{VFD,yr}$	Energy consumption per year, VFD control method (kWh, MWh)
F	Rated loss factor
g	Gravity (m^2/s)
h	Number of operational hours per day
HIC	Halving interval for an insulation class (°C)
I	Initial investment (€)
l	Percentage of nominal flow
L_{100}	Percentage of lifetime at rated load (100%)
L_x	Percentage of lifetime at partial load (%)
N	Speed (rpm)
n	Number of operational days per year
P	Power(kW)
$P_{p/f,j}$,	Actual pump/fan input power (shaft power) (kW)
$P_{p/f,o}$	Pump or fan output power (kw)
Q	Flow (m^3/s, m^3/h)

r	Discount rate
t	Lifetime or depreciation period of the equipment
T_c	Total allowable temperature for an insulation class (°C)
T_x	Hot-spot temperature for an insulation class (°C)
w_o	Actual motor output power (kW)
w_{rated}	Rated motor output power (kW)

Acronyms

AC	Alternate current
DC	Direct current
EB	Energy benefits
EF	Emission factor (tonnes CO2/kWh)
ETS	Emission trading system
GHG	Greenhouse gases
IGBT	Insulated gate bipolar transistors
IRR	Internal rate of return
LV	Low voltage
MV	Medium voltage
NEB	Non-energy benefits
NPV	Net present value
PBP	Payback period
PWM	Pulse width modulation
RQ	Research question
SQ	Sub-question
VFD	Variable frequency drive
VSD	Variable speed drive

Chapter 1. Introduction

Efforts around the globe to combat climate change have increased in the last couple of years by the introduction of different agreements. Even though both public and private sectors have strengthened their actions to reduce greenhouse-gases (GHG) emissions and energy use, literature proves a shortfall in these strives. Reports as The Emissions Gap Report released by the United Nations Environment Program (UNEP) show that public policies and investments in energy efficiency projects taking place nowadays might be insufficient to meet the goals of such agreements (UNEP, 2017).

As stated by the International Energy Agency (IEA) in the World Energy Outlook (WEO) 2016, energy efficiency needs to be at the heart of any strategy to guarantee secure, sustainable and inclusive economic growth. Although it is one of the most cost-effective ways to enhance security of energy supply, to boost businesses' competitiveness and to reduce the environmental burden of the energy system, an energy efficiency gap described as the discrepancy between the optimal and actual implementation of energy measures has been observed (Backlund, Thollander, Palm, & Ottosson, 2012; IEA, 2016)

In an effort to cope with this energy efficiency gap and promote measures in the industry and services sectors, different projects and researches are being carried out. The project Multiple Benefits (M-BENEFITS) for instance, with the collaboration of government organizations, private companies and universities, aims to train and build the capacity of energy-efficiency experts to evaluate all benefits (i.e. not only the energy-saving benefits) in energy efficiency projects. This non-energy benefits (NEB's)[1] approach enhances the attractiveness of energy investments and the likelihood for project implementation as a large share of energy efficiency is not seen as cost-effective and productively favourable when the analysis accounts for only energy savings as benefits (Anonymous, 2017; Pye & McKane, 2000).

A special focus has to be given to the industry sector because its potential for energy efficiency improvements. The industry sector represents 36% of the global final energy consumption and 24% of total CO_2 emissions (IEA, 2017). Despite the different energy uses, electric motor drive systems (EMDS) account as the largest electricity consumers in industrial facilities (Lawrence et al., 2010). As shown in Fig. 1, EMDS represented a 48.2% of the electricity consumption in manufacturing industries[2] around the United States in 2014 (U.S. Energy Information Administration [EIA], 2014).

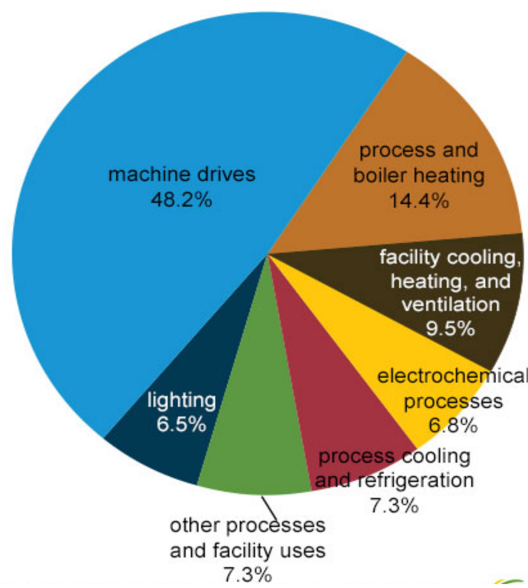


Figure 1. Electricity consumption of U.S. manufacturing industries by major end uses (U.S. EIA, 2014).

[1]Co-benefits, multiple benefits, productivity benefits and ancillary benefits are also terms used to describe non-energy benefits.
[2]The estimates of energy use from the EIA surveys include the manufacturing industries according to the definition of the North American Industry Classification System (NAICS). https://www.census.gov/eos/www/naics/2017NAICS/2017_NAICS_Manual.pdf

Codes and standards focusing on the use of efficient electric motors have been developed and successfully adopted in different contexts since the 1990's. The International Electrotechnical Commission (IEC) 60034 series of standards for example, which classify the efficiency of single-speed motors from IE1 (standard efficiency) to IE4 (super-premium efficiency), form the basis of the minimum energy performance standards (MEPS) that are now in force in most advanced economies and many developing countries (IEA, 2015). Yet, standards and regulations on the extended product other than the motors themselves have been limited and not fully exploited (Tanaka, 2011).

Because of this reason, the biggest potential for increasing energy savings does not lie in improving the efficiency of the motor itself, but in improving the performance efficiency of the EMDS (McKane & Hasanbeigi, 2011). It requires a system-wide approach that encompasses not only strict regulation of motors, but also larger uptake of variable frequency drives (VFD's)[3] and the implementation of measures to enhance the efficiency of the system as a whole (IEA, 2016).

There are several industrial processes requiring the motor to operate at different speeds. About two-thirds of the motors in industrial use are for pump and fan applications which do not need constant motor speeds (Saidur, 2010). Because most electric motors today are fixed-speed induction motors, the potential of energy savings is very high (Saidur, Mekhilef, Ali, Safari, & Mohammed, 2012). In a fan system, for instance, the fixed-speed motor is chosen to meet the maximum air flow requirement and this flow is then regulated via a throttle: for most of the time, the airflow is invariably higher than it needs to be, thus keeping the motor running at full load and consuming electricity at its most (IEA, 2016).

VFD's are precisely controllers that improve energy efficiency by matching the rotating speed and the torque of the motor to meet any required load, eliminating the need of extra mechanical components to regulate flows, and reducing the power delivered by the motor (IEA, 2015).

Several researches evaluating the benefits of VFD's have been carried out (e.g. De Tarso, Bezerra, Silva, Gomes, & Salvino, 2015; Mallick & Paul, 2014; Su, Chung, & Yu, 2014). However, these have focused on the quantification of the energy savings brought by its implementation, in different applications, and not on the NEB's (e.g. product quality, higher flexibility, reduced maintenance costs) they can bring.

Due to these reasons, the present research focuses on the investigation and quantification of the NEB's that can be obtained by the implementation of VFD's in pump and fan applications at the global industry sector[4], and from a company perspective. That said, the main Research Question (RQ) is introduced:

How can accounting the NEB's in pump and fan applications increase the economic profitability of VFD's energy efficiency projects at industries, and influence investment decision-makers?

In order to answer the main RQ, the following Sub-Questions (SQ's) are addressed:

1) *What are the NEB's brought by the use of VFD's in pump and fan applications?*

[3]Also called variable speed drives (VSD's), adjustable speed drives (ASD's) or frequency converters, a VFD is a motor controller that regulates the speed and rotational force, or output torque of an electric motor by varying the frequency and voltage of its power supply (Saidur et al., 2012).

[4]Industry definition according to the North American Industry Classification System (NAICS). https://www.census.gov/eos/www/naics/2017NAICS/2017_NAICS_Manual.pdf

By answering this question, the benefits brought by implementing VFD's in pump and fan applications are firstly identified.

2) *To what extent can such NEB's be quantified?*

Next, after the NEB's applicable to such applications for the global industry sector are recognized, the extent of their quantification and/or monetization is assessed.

3) *To what degree can a common calculation method, applicable to different contexts, and able to assess the economic profitability of such NEB's be developed?*

After answering Research Questions 1) & 2), it is determined if a calculation method applicable to different industries and pump/fan applications, that evaluates the cost effectiveness of the NEB's can result from the quantification of the benefits. A model compiling this calculation method is then examined to be developed as an outcome or end product of the current research.

Overall, by answering the RQ and SQ's, this research aims to not only stimulate the implementation of VFD's by highlighting the NEB's, but also to further encourage governments and standardization bodies to realize their advantages and develop the missing standards and regulations regarding VFD's.

In the next chapter Definitions and Scope, important theories, key-concepts, definitions referred, and the scope of this thesis research are described in depth. In the following chapters, the way the SQ's are answered and the results obtained by answering each question are explained. After this, a general discussion, the assumptions made in the research, a sensitivity analysis and recommendations for further investigation are given. Lastly, the conclusions of the master thesis are presented.

Chapter 2. Definitions and Scope

In this chapter, the theory and definitions that form the basis of the current research, together with the scope of analysis are provided.

2.1. Non-energy Benefits

According to the Energy Efficiency Directive 2012/27/EC, energy benefits (EB's) or savings are the amount of saved energy determined by measuring and/or estimating consumption before and after implementation of an energy efficiency measure, whilst ensuring normalisation for external conditions that affect energy consumption (The European Parliament and the Council of the European Union, 2012).

"Non-energy benefits are therefore the benefits related to industrial energy efficiency investments, beside energy savings, that are quantifiable at a varying level and arise in a short- and/or long-term perspective" (Rasmussen, 2017). They include among others lower maintenance costs, increased production yields and reduced CO_2 emissions.

NEB's have gained attention since the energy savings deriving from energy efficiency projects have been found to not be attractive enough to appeal investments decision makers at industries (Pye & McKane, 2000). NEB's can be translated into cost reductions and incorporated in investments analysis; increasing the cost-effectiveness of projects by improving profitability indicators such as payback periods (PBP) or internal rates of return (IRR) (Lung, Mckane, Leach, & Marsh, 2005). Nevertheless, the greatest advantage of highlighting these benefits is their connection to the core businesses and to the competitive advantages of firms (Cooremans, 2011).

In order to appeal a company, energy efficiency projects have to be perceived to contribute their core business activities (Cooremans, 2015). NEB's can precisely achieve this goal by relating themselves the competitive advantage of a firm (Cooremans, 2015). Competitive advantage means how a company performs better than its competitors. Cooremans redefines this concept and assigns three interrelated constituents to it: costs, value proposition and risks.

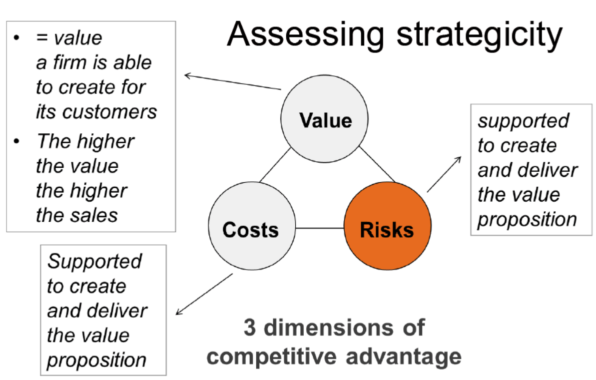


Figure 2. The three dimensions of the competitive advantage term (Cooremans, 2011)

According to Hassan (2012), value proposition is an explicit promise made by a company to its customers that it will deliver a particular bundle of value creating benefits. Costs are then the monetary expenditures required to create this value and risks are the ones encountered while creating and delivering the value proposal to the customers (Cooremans, 2015).

Evaluating the cost reductions, the value proposal contribution and the risk reduction that NEB's can bring is equivalent to assess the contribution of energy efficiency investments to the competitive advantage (i.e. "strategicity") of a firm (Cooremans, 2015). Thus, such evaluation can increase the strategic character and attractiveness of energy efficiency (Cooremans, 2015). (See Fig. 2).

NEB's can be used then to overcome barriers such as uncertainty, irreversibility, slow rate of return and technical risk; found to be the main barriers for energy efficiency investments (Cooremans, 2011; Rasmussen, 2014).

Different categorizations and frameworks to study and quantify NEB's have been proposed (e.g. Cooremans, 2015; International Energy Agency, 2014; Rasmussen, 2017; Worrell, Laitner, Ruth, & Finman, 2003). As stated by Rasmussen (2017), a definition and categorization serves as a bridge between the process of identifying and quantifying NEB's related to a specific energy efficiency project. Cooremas (2017) and Rasmussen (2017) therefore provided different categorizations to simplify the inclusion and description of NEB's in energy efficiency business cases.

Worrell et al. (2003) on the other hand, proposed a framework consisting of four steps to evaluate and quantify NEB's related to energy efficiency technologies. The four steps mentioned in Worrell et al. (2003) framework are:

1. Identify and describe the non-energy benefits associated with a given measure.
2. Quantify these impacts as much as possible.
3. Identify all the assumptions needed to translate the benefits into cost impacts.
4. Calculate cost impacts of non-energy benefits.

The categorisations and framework by Cooremans, Rasmussen and Worrell et al. facilitate the description of NEB's and allow a transparent evaluation process in investments analysis. Due to this reason, their scientific contributions served as the foundation to identify and quantify the additional benefits related to VFD's.

Furthermore, because prices are common notions easy understood by everyone, this research focuses in evaluating the costs reduction brought by the NEB's (Cooremans, 2015). Nevertheless, the value proposal and/or the risk reduction contribution of each benefit is pointed out, as assessing the dimensions of the competitive advantage term can positively influence energy efficiency investment decisions at companies.

2.2. Variable Frequency Drives

A VFD is an electronic controller that varies the speed and torque of an electrical motor (Saidur et al., 2012). A drive system is a combination of a VFD, a motor, and any motor mounted auxiliary device such as a pump or a fan (See Fig. 3). It provides means of adjusting the speed of a mechanical load coupled to the motor by varying controllable variables such as voltage, current or frequency (NEMA, 2015; Sylwester, Wasilewski, Dawidowski & Szweczyk, 2016).

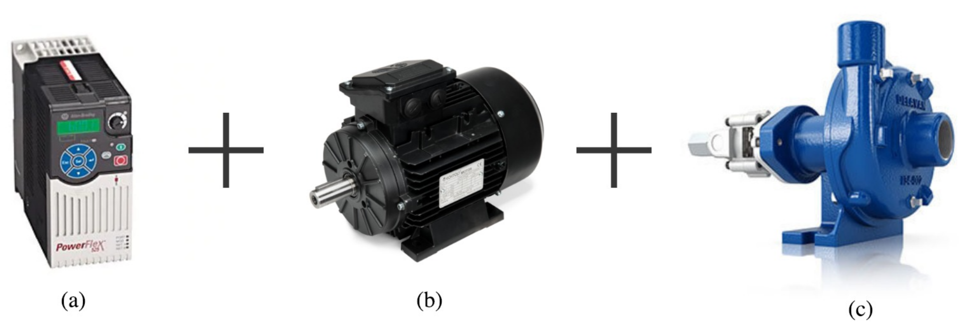


Figure 3. Basic components of a drive system. (a) VFD. (b) Electric motor. (c) Driven equipment.

VFD's can be classified in two categories according to the type of power source: direct current (DC) and alternate current (AC). Furthermore, AC drives are classified by the type of motors they drive into synchronous motors and induction motors, and either single or three-phase. Drives can also be categorized by their voltage and power ranges in Low Voltage (LV) and Medium Voltage (MV). LV typically includes voltages less than 750 volts and powers less than 375 kW or 500 HP. MV covers voltages between 0.4 MW to 40 MW and powers between 2.3 kV to 13.8 kV. (Domijan & Kmbriz-Santander, 1992; Sylwester et al., 2016).

Typically, a VFD consists of a rectifier, a DC-link and an inverter section (See Fig. 4). In the rectifier section, the AC voltage supply at a fixed frequency (usually 50 Hz or 60 Hz) is converted to DC voltage by an arrangement of diodes or insulated gate bipolar transistors (IGBT). Next, in the DC-link section capacitors acting like filters help to smooth the wave and produce a clean DC supply. Lastly, the inverter section sequentially switches this DC into AC of variable frequency through the load. This is usually made by IGBT's which are rapidly switched on and off by a pulse width modulation (PWM) technique, resulting in a variable voltage and current waveform with variable width (i.e. variable frequency) as shown in Fig. 5 (Natural Resources Canada, 2015b; Saidur et al., 2012; Scheuer, Schmager, Krishnan, Khaleej, & Refinery, 2007).

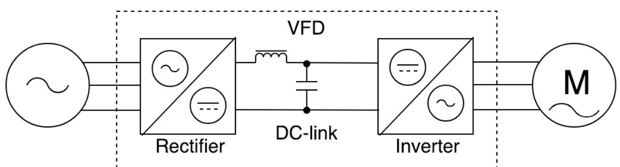


Figure 4. Basic components of a VFD.

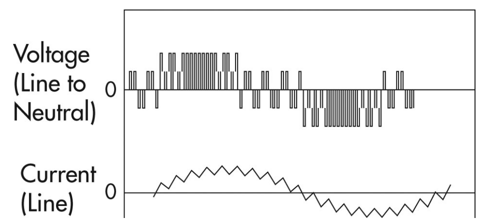


Figure 5. Current and voltage output graphs of a PWM VFD (Natural Resources Canada, 2015)

Depending on their application, drive loads can be related to speed and torque, and classified by: (Natural Resources Canada, 2015; Schneider Electric, 1995)

- Variable torque: the driving torque is quadratically and varies directly with the speed squared. In these applications the power varies directly with the speed cubed, meaning that at small variations of speed bring great savings in power (i.e. at half speed, approximately only one eight of power is required). The relations between reduction in speed, flow, pressure and horsepower are described by the so-called Affinity Laws (See Eq. 1). Examples of variable torque applications are centrifugal pumps and fans.
- Constant torque: the driving torque is constant and not a function of the speed. In constant torque applications the power varies linearly proportional to the speed. Typical applications of constant torque applications are conveyors, extruders and mixers.
- Constant horsepower: the driving torque varies inversely with the speed and the power remains constant. As a consequence, these applications do not offer energy savings at low speeds. Machine-tools such for drilling and milling are examples of this type of application.

Variable torque applications enable a greater energy savings potential comparing to constant torque applications. Additionally, constant torque loads cause motors high currents on low speeds comparing to variable torque applications.

Equation 1. Affinity laws.

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \qquad \frac{\Delta P_1/H_1}{\Delta P_2/H_2} = \left(\frac{N_1}{N_2}\right)^2 \qquad \frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3$$

Where:
N = speed (rpm)
Q = flow (m^3/h, gpm)
ΔP/H = pressure difference or head (m, ft/Pa, psi)
P = power (w)
Note: Subscripts 1 and 2 indicate the initial and new capacity conditions, respectively

Because pump and fan applications represent around 40% of the motors electricity consumption in the industry sector (Aníbal T De Almeida, Fonseca, & Bertoldi, 2003; Fleiter & Eichhammer, 2011), and as variable torque loads are the best candidate applications to apply VFD's for energy savings, the scope of this research is limited to researching the NEB's of VFD's in pump and fan applications. Moreover, since three phase LV AC induction motors dominate the market and are the type of motors most used with VFD's (A.T. De Almeida et al., 2003), the thesis focuses in studying applications with these motor characteristics.

2.3. Profitability Indicators

According to Tulsian (2014), profitability is the ability of a given investment to earn a return from its use. In this context, the profitability of an energy efficiency investment can be described as the relationship between the capital invested and the income that the benefits related to this investment can bring in return (Cooremans, 2012).

Considering that the PBP and IRR appear to be the most used profitability indicators in energy efficiency projects at industry (Boland & Duquesnoy, 2012; Nehler & Rasmussen, 2016), the economic impact of the NEB's in this research is assessed by comparing these two indicators to a reference case with only EB's. In other words, the difference in PBP and IRR by a scenario considering EB's and another considering EB's with NEB's together, allows the evaluation of the profitability potential of the NEB's. This potential is therefore assessed in unit terms of "reduction in years" for the PBP, and "increase of the rate of return" for the NPV.

Payback Period

Although the PBP is a profitability indicator which is only based on the risk of an investment (i.e. it does not take the lifetime into account), it appears to be the financial method most used by firms to evaluate energy-efficiency projects (Cooremans, 2011; Nehler & Rasmussen, 2016; Sandahl & Sjögren, 2003). It represents the time required to recover the initial invested capital and it is expressed in years or months. It is calculated by the following equation (Blok & Nieuwlaar, 2017):

Equation 2. PBP.

$$PBP = \frac{I}{B\text{-}C}$$

Where:
I = initial investment of the project (€)
B = annual benefits (€)
C = annual costs (excluding capital costs) (€)

PBP thresholds below 3.5 years have been previously reported from researches as an average value required by firms (Cooremans, 2011; Harris, Anderson, & Shafron, 2000).

Net Present Value (NPV)

The NPV is the discounted value of the investment cash flows, assessed on the life cycle of a project, less any initial investment costs (Cooremans, 2011). The discount rate represents the minimum requirement, by the investor, of return on the investment, which is based on the cost of capital for the firm and on the risk attached to the project: the higher the risk, the higher the discount rate, the lower the NPV, the less financially attractive the investment (Cooremans, 2011). A project is usually considered attractive if the NPV is positive. The NPV is calculated by the following equation (Blok & Nieuwlaar, 2017):

Equation 3. NPV.

$$NPV = -I + \frac{B-C}{\alpha}$$

Where:
I = initial investment of the project (€)
B = the annual benefits (€)
C = annual costs (€)
α = capital recovery factor (%)

Equation 4. Capital Recovery Factor.

$$\alpha = \frac{r}{1 - (1+r)^{-t}}$$

Where
r = discount rate (%)
t = lifetime or depreciation period of the equipment (years)

The internal rate of return (IRR) is the discount rate at which the net present value of an investment is equal to zero (Cooremans, 2011). An IRR of 26% resulted to be the required average value in energy efficiency related projects found in previous studies (Boland & Duquesnoy, 2012; Harris et al., 2000).

2.4 Scope

To allow simplicity in the calculations, the research focuses on the European continent. Nevertheless, all the findings resulting from this study are applicable to other geographical locations.

Chapter 3. General Methodology Framework

The methodology to answer the main RQ and its consequent SQ's was based on the three stages shown in Fig. 6. This method was founded and further developed from the four-step framework proposed by Worrell et al. (2003) to evaluate NEB's of energy efficiency technologies.

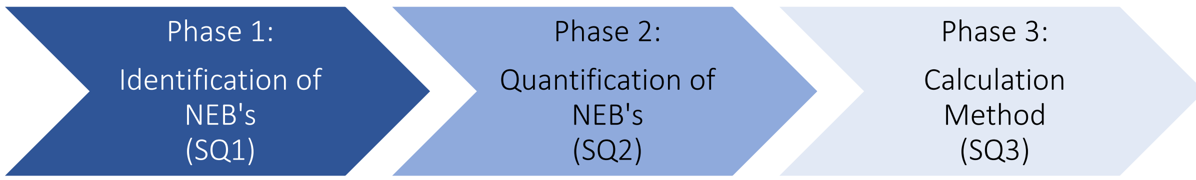


Figure 6. General research methodology.

The following chapters are organized as follow. First, the methodology carried out to identify the NEB's is explained (Chapter 4). After, the NEB's found to be brought by VFD's at pumps and fan applications are presented (Chapter 5)[5]. Next, the method to quantify the benefits applicable to all the pump and fan applications (i.e. not case specific) is determined (Chapter 6). Following, a theoretical study case is conducted to show the potential economic impact of the benefits (Chapter 7)[6]. Lastly, the calculation method to quantify and asses the profitability of the EB's and NEB's in any pump and fan application, together with the model compiling the calculation method, are presented and explained in detail (Chapter 8 & Chapter 9)[7].

[5] Chapter 4 and 5 represent the Phase 1 of the methodology.
[6] Chapter 6 and 7 represent the Phase 2 of the methodology.
[7] Chapter 8 and 9 represent the Phase 3 of the methodology.

Chapter 4. Identification of NEB's (SQ1)

A literature review consisting of two parts (General NEB's and Specific VFD NEB's) was conducted to identify and describe the benefits related to both energy measures in general and to VFD's. The general review was performed to identify existing categorizations or frameworks associated with NEB's. This was accomplished to have a general picture and a benchmark of the benefits that VFD's can bring. The specific review was therefore carried out to identify the particular benefits brought by VFD's in pump and fan applications.

4.1. General NEB's Literature Review

The General NEB's data collection consisted on a literature review of scientific articles. Different categorizations and frameworks were identified but reduced to the most complete ones proposed by Cooremas (2017) and (Rasmussen, 2017).

In Cooremans' categorization list, she identifies a total of 50 generic NEB's by seven different categories: waste, emissions, production, operations and maintenance, working environment, risk reduction and others (See appendix A). She provided the evaluation nature of the benefits as by quantitative or qualitative and gave examples of indicators to measure their gains (e.g. "% of default pieces/produced pieces" for the "Improved equipment performance" NEB). Lastly, she assessed the contribution of the benefits to the operational excellence of companies and their contribution either to risk reduction, value increase and/or costs decrease (constituents of the competitive advantage concept of a firm) (Cooremans, 2015).

Similarly, Rasmussen proposed a categorization and framework of NEB's based on a systematic literature review. First, she methodically reviewed the three terms normally used to describe additional benefits of energy efficiency measures (ancillary benefits, co-benefits and NEB's). This was made to establish and define the term, that among the energy efficiency literature was most suitable to use in relation to industrial energy efficiency investments. She comprised a total final sample of 34 papers fully read using the database Scopus. The term NEB's resulted to be the most adequate term to be used in the context of industrial energy efficiency. On the other hand, the terms ancillary benefits and co-benefits, with the highest number of hits in papers regarding the energy field, were found to be frequently applied to describe environmental and health benefits instead.

Next, after reviewing the existing classifications of NEB's found in literature (e.g. IEA, 2014; Pye & McKane, 2000; Worrell et al., 2003), Rasmussen compiled a list of 57 NEB's divided in 6 different categories: work environment, production, operations and maintenance, waste, emissions/environment and other (See Appendix B). In order to prevent the rejection of some important but intangible benefits such as the ones incurring in an improved work environment, she didn't categorize the benefits into being quantifiable or non-quantifiable but introduced a new framework to categorize the benefits taking into account a scale of quantifiability. Moreover, she also considered the time the benefits are expected to occur at either short or long term so the NEB's can be evaluated with precision and reduced uncertainty.

After both Cooremans' and Rasmussen's lists were reviewed, the NEB's were compared in order to comprehend a combined list of NEB's. A total of 61 benefits divided in seven categories were compiled (See Appendix C). The categories chosen in this list were the ones used by Cooremans as the additional "Risk reduction" category in her list make the categorization of the benefits more specific.

The lists were combined taking into account the different phrasings of the benefits, so double counting and redundancy of the benefits could be avoided. The NEB's "Improved lighting (visual comfort)" and "Reduced glare/eyestrain" for example, were combined in the "Improved lighting (visual comfort)" benefit as both benefits depict the same. As stated before, this combined list served as a reference to identify the specific NEB's that could be brought by the use of VFD's in pump and fan applications.

4.2. Specific VFD NEB's Literature Review

The specific VFD NEB's data collection was focused on pump and fan applications and divided in two parts: a systematic literature review and a surveys phase. In the literature review, scientific articles, reports, study cases and literature from VFD's manufacturing companies were investigated. In the survey phase, questionnaire surveys were conducted to further identify specific benefits, and to validate the findings from literature.

4.2.1. Systematic Literature Review

The scientific articles, reports and study cases literature review was carried out using the database Scopus. The search was set to search for ¨Variable Frequency Drives Benefits" within the title, abstract and keywords of the papers. It resulted in the following search string: TITLE-ABS-KEY (Variable AND Frequency AND Drives AND Benefits). No further filters (e.g. document types, subject areas, access type) were applied. The number of hits by these searching parameters resulted in a total of 319 papers as per December 2018. These papers were firstly analysed by their title. If the title of the paper was considered to not match the scope of this research, its review was excluded. Secondly, their abstracts were reviewed with the same purpose. In case the papers were not excluded by these two conditions, they were fully read to identify and analyse the NEB's and the context of their appearance. If such papers were not available through Scopus, a search online using other databases was performed (e.g. IEEE Xplore, Google Scholar).

Similarly, the search "Variable Speed Drives Benefits" with string TITLE-ABS-KEY (Variable AND Speed AND Drives AND Benefits) was performed. In order to avoid double counting, the results of this search string were exported and compared to the ones obtained by the search "Variable Frequency Drives Benefits", using Microsoft Excel and the VLOOKUP formula. After comparing what papers had been already reviewed with the first string, and following the same methodology, additional papers were read for the alternate term VSD's. A total number of 48 papers resulting from both search strings were found available and fully read. The summary of NEB's cited per paper reviewed is shown in Appendix D.

The literature review from VFD's manufacturing companies consisted of a study of commercial LV AC VFD's brochures and webpages from the largest manufacturing companies of electrical equipment: Siemens, Schneider Electric, ABB, Rockwell Automation and Danfoss. This review also included study cases carried out by these manufacturing companies and allowed to further identify what NEB's are brought by VFD's. In a similar way as with the review of scientific literature, the VFD's manufacturers literature study resulted in a summary table of NEB's cited per manufacturing company (See Appendix E).

4.2.2. Surveys

After the literature review phase was carried out, surveys were conducted to working professionals in the field of VFD’s. This was made to add validity to the findings obtained by the literature review.

These surveys consisted of three open questions and a checkbox questionnaire, where respondents were asked to select, based on their experience, what NEB’s from the combined list of Cooremans and Rasmussen are brought by VFD’s in pump and fan applications. These surveys were conducted via the SurveyMonkey platform and included the following four questions:

1. What is your current job position?
2. What company are you working for?
3. According to your experience, what non-energy benefits from the following list can be brought by the implementation of VFD’s in pump and fan applications?
4. Is there any other non-energy benefit that was not listed and that can be brought by the VFD's in the same applications?

Responses from a total number of 6 professionals in the field of automation and drives from the companies ABB and Rockwell Automation were obtained (See Appendix F).

After analysing the results of the surveys, it was validated that the benefits selected by the respondents matched the same benefits found in the literature review part. Furthermore, no additional benefits were answered in the 4th question by the participants. This gave validity and integrity, supported by professionals, to the findings obtained in this first phase of the research.

In the next chapter and following the categories of NEB’s by Cooremans, the NEB’s that were identified to be brought by the use of VFD’s are listed and described.

Chapter 5. List of NEB's (SQ1)

The benefits identified to be brought by VFD's in pump and fan applications, the extension of their citation[8] in the included literature, and their contribution to either the costs reductions, value proposal and/or risk reduction as per Cooremans are presented in Table 1.

Table 1. Number of times VFD's NEB's of pump and fan applications occur in the reviewed literature and their contribution to costs decrease, value increase and/or risk reduction.

Category	NEB	Citation count	Costs decrease	Value increase	Risk reduction
Production	Improved process control	23	X	X	X
	Improved product quality/consistency	11	X	X	X
	Improved production reliability	9	X	X	X
	Increased productivity	9	X	X	X
	Improved equipment performance	6	X	X	X
	Improved flexibility of production	5	X	X	X
	Shorter production cycles (shorter process cycle times)	2	X	X	X
	Increased product yields	1	X		X
Operations and maint.	Reduced wear and tear on equipment and machinery	28	X		X
	Reduction in operation and maintenance costs	18	X		
	Extended life of equipment	17	X		
	Reduced malfunction or breakdown of machinery and equipment (downtimes)	14	X	X	X
	Improved temperature control	5	X	X	X
	Reduction in labour requirements	3	X		X
Waste	Reduced water losses and bills	2	X	X	X
Emissions/environment	Reduced GHG emissions	13	X	X	X
	Reduced costs of environmental compliance	0	X		X
Work environment	Reduced noise (auditive comfort)	12			X
	Improved worker/installation safety	9	X	X	X
	Improved temperature control (thermal comfort)	4	X	X	X
Other	Elimination of additional equipment parts*	9	X		X
	Improved power factor*	8	X		X

**NEB's not found in the combined NEB's list from Rasmussen's and Cooremans'.*

The most cited NEB's in both scientific and manufacturers literature are the "Improved process control", "Improved quality", "Decreased noise", "Reduced tear and wear on equipment machinery" and "Reduced emissions". These findings match the results of the beforementioned systematic literature review carried out by Rasmussen (2017), where the citation number of NEB's from energy efficiency measures was also registered. In a similar way as in her research, the benefits in the categories "Operation and Maintenance" and "Production" are the most frequently cited in literature.

It is also noteworthy to mention that Cooremans and Rasmussen did not include two NEB's brought by the use of VFD's in their categorization lists. The two NEB's not matching the combined list were "Improved system power quality" and "Reduced additional equipment parts", allocated to the category "Other".
In the next subchapters, the NEB's are described in detail following the Cooremans' categorization. The

[8] In order to avoid double counting, the numbering of the benefits in the studied literature was made taking into account their literally citation, and not their relation to other benefits. (e.g. if the benefit "Reduced wear and tear on equipment and machinery" was cited, the benefit "Extended life of equipment" was not counted for the citation). For the citation of benefits which did not match the literal phrasing of the benefits in the list, the closest related benefit was accounted for.

order the benefits are described does not match their citation number in literature, but their relation to each other and their order of appearance (e.g. the benefit “Reduced wear and tear…” was presented first as it results in an “Extended lifetime of equipment” benefit).

The description of the benefits is made in line with the recommendations given from Worrell et al. (2003) at the first step of their framework. Lastly, in order to make a transparent and more credible evaluation of NEB’s, the potential drawbacks brought by the introduction of VFD’s are described next after (Worrell et al., 2003).

Although the research focused in the industry sector, some of the benefits are also applicable to VFD’s in pump and fan applications at the building sector (e.g. HVAC systems).

5.1. Production

Increased productivity

Process equipment is usually designed to handle different capacities and provide future productivity increases (ABB, 2011). With constant speed equipment such as fixed speed motors, those changes in performance and capacities are not possible. With VFD’s, speed can be variated to fit the demand of an existing process and their future expansions, thus increasing the product output possibilities at no extra cost (ABB, 2011).

Additionally, VFD’s can bring an increase on the reliability of the motor, the driven equipment and the accessories of the system (Sylwester et al., 2016). This can enhance an increase in production outputs by decreasing shutdowns due to broken or damaged equipment.

In the gas production site of las Cira-Infantas in Southern Colombia for instance, the implementation of VFD’s together with a control software eliminated the shutdowns due to the gas locking effect in electrical submersible pumps (ESP’s); increasing the oil production rates a daily 14% (Chira et al., 2017).

Improved process control

In addition to the improvements in process control that drives bring by controlling the speed and torque of the motor in an accurate way, VFD’s offer other built-in features that enhance a better process control (ABB, 2011). Although these features variate among drive manufacturers, the most common ones are (ABB, 2011):

- Inputs and outputs feature. Information about the process performance (i.e. inputs) can be fed to the drive and vary the control (i.e. outputs) of the motor accordingly.
- Reversing feature. Some applications such fans in cooling towers require the driven equipment to operate in reverse in order to complete a defrost cycle when the outside temperature is very cool (Danfoss, 2003). VFD’s have the ability to reverse the motor rotation by simply pressing a button.
- Acceleration and deceleration ramp times feature. Certain processes require to accelerate and decelerate in a controlled and consistently way. VFD’s have a ramp time feature that allow the user to increase or decrease the speed over a certain amount of time. In pumps for instance, a ramping acceleration is required to avoid the water hammer effect, which is a pressure surge caused by abrupt changes in the flow rate.

Comparing the control features of VFD’s to mechanical solutions such as damper/throttles, On/Off or bypasses, VFD’s provide a smother and much more accurate way of controlling a process. VFD’s can even control speeds and torques with accuracies of 0.1% (Scheuer et al., 2007).

Improved product quality/consistency
Improved quality of the end-product can be achieved by enabling better control and an optimal performance of the process. This can result in a reduction of scrap or waste material, compared to traditional control methods, as products can comply conformity specifications at a higher rate (ABB, 2011).

In the production of hard woods such as oak for instance, the volume of air flow provided by fans has to be precisely variated during the kiln drying process of the lumber. The air flow rates depend on the factors such as the type of wood and its moisture content, requiring lower air flows during the production cycle as the moisture content decreases. VFD's can precisely provide the range of flows required in this process. By implementing VFD's in their fans, the manufacturing company Matthews Casket located in York, U.S., improved the quality and consistency of their products. (Sikora, 2017).

Increased production yields
As mentioned before, improved process control and product quality translates into a reduction of scrap or product waste, resulting in an increase of production yields.

The Cascade Energy Engineering company documented significant reduced mass losses and firmness in apples at fruit refrigerated facilities (Anderson, Collins, Cortese, & Ekman, 1996). These benefits were found after installing VFD's for the control of evaporator fans in a warehouse with controlled environments.

Improved flexibility of production
Production flexibility refers to the ability of a production system to respond effectively and efficiently to external uncertainties, so as to a produce customised products of high quality (Jain, Jain, Chan, & Singh, 2013). As stated before, drives can increase the production output levels when demand requirements vary from forecast, providing operation flexibility. Moreover, electronic motor control has the ability to adapt to changing work programs, thus to different end-product types, providing a large product range (Jain et al., 2013).

Improved equipment performance
The best efficiency point (BEP) in centrifugal equipment is defined as the maximum value of efficiency at a certain flow rate (Gulich, 2014). A deviation of this BEP results in energy wastage and can bring vibrations and other mechanical negative effects to the equipment (UNEP, 2006).

With conventional control flow techniques such as throttle valves or dampers, the efficiency is decreased by generating resistance, while keeping the same power consumption. Because with VFD's the flow decreases together with the power consumption, and the pressure and flow can be adjusted to operate close to the BEP's, the performance of the equipment can be increased (Pemberton, 2003).

Improved production reliability
Because the wear of the driven equipment, bearings, seals and any other related accessory is reduced while working close to the BEP's, less maintenance and a reduction in downtimes can be obtained by the use of VFD's. In other words, the system can be available more time, increasing the reliability and capacity utilisation of production.

In addition, VFD's lower the requirement of components in the system; thus, decreasing the chances of equipment failure or broken machinery and increasing the production reliability.

Shorter production cycles (shorter process cycle times)
Not only can the use of VFD's bring savings in production cycle times by preventing downtimes and machinery breakdowns, but also by improving the control of a process.

In the research facility of USCS (United States Cold Storage) in Fresno, California, a new methodology was developed and tested to control refrigeration processes using VFD's to modulate the speed of blast freezing fans', depending on the product temperature. Air blast freezing is a process where the heat of products is removed in a relatively short period of time (Dietrich, Lynch, Snyder, & Jones, 2010). This new methodology implemented drives and a new computerized control algorithm using measures of the product's temperature. It proved to lead to considerable technical potentials without compromising cooling requirements, compared to traditional control methods with no speed control.

In addition to the energy savings, a decrease in cycle times was observed while freezing pallet layers of ground beef. It was demonstrated that the blast freezing process could be achieved in 15 hours less than the current process time (Dietrich et al., 2010).

5.2. Operation and maintenance

Reduced wear and tear on equipment and machinery
The introduction of VFD's brings a reduction in wear and tear over the motor, the driven equipment and the machinery by different means.

First, a reduction in operating speeds in pumps and fans naturally reduces the wear of the motor and its driven equipment. Lower speeds translate into lower temperatures at the motor and lower pressures in the equipment, diminishing the electrical and mechanical stresses (A.T. De Almeida et al., 2003b).

Secondly, while in a direct-on line (DOL) connection, the current drawn at the start of the motor can be up to 7 times the nominal current, the VFD's act as soft starters ramping up to full speed and limiting the start-up currents to no more than the nominal values (Scheuer et al., 2007). This enhanced soft start feature reduces the power system voltage drop and the surge pressures in pipelines caused by the abrupt starts and stops, thus minimizing the electrical stress at the motor and the mechanical shocks at the equipment (Ramirez & Yu, 2012).

Lastly, the replacement of mechanical devices to regulate the flow of a fluid by VFD's, the operation close to the BEP and the ability of the drives to avoid critical resonant frequencies lead to less vibrations and resonances in the ducts or pipes conducting the fluid, avoiding a premature wear of the system components (Lawrence & Heron, 2016).

Reduced malfunction or breakdown of machinery and equipment
The reduction in wear and tear by VFD's leads to a reduction in downtimes due to malfunction or breakdown of the equipment.

At the company Enbridge Liquid Pipelines for example, a reliability study demonstrated that the probability of failure in pumps and motors driven by VFD's is lower compared to the ones without VFD's (Ferrari, 2016). In this company, 50% of the pipeline network used to process heavy crude oil is operated by pumps fitted with VFD's.

From their Computer Maintenance Management Systems (CMMS) a set of 154 pumps (81 equipped with VFD's; 73 without VFD) were considered. A mean time between repair (MTBR) of 995.20 days for pumps equipped with VFD's and 603.43 days without VFD resulted from the reliability analysis, indicating a higher operational reliability (i.e. longer time between failures) of 65% for pumps controlled by VFD's.

Similarly, 171 electric motors driving the pumps were analysed from the CMMS. From the reliability and failure calculations performed, it was concluded that the motor with VFD's will experience 73% less total downtime than the motor without VFD in a 45 years operation time scenario. In terms of MTBR, a higher operation reliability of approximately 25% was observed. (Ferrari, 2016).

Reduction in operation and maintenance costs
A reduction in downtimes, together with the simplification of the system due to the elimination of mechanical parts, represent a reduction in the maintenance service required over the equipment and a evidently decrement in the O&M costs (Lawrence & Heron, 2016). Overall, mechanical components such as valves or dampers require more maintenance than VFD's (ABB, 2011)

Although not quantified or monetized, different projects among literature have reported reductions in maintenance costs after equipping pump or fans with VFD's (Chira et al., 2017; Dolores A. & Moran L., 2001; Worrell et al., 2010)

Reduction in labour requirements
On-site labour requirements can be diminished by reducing the downtimes caused by failures or breaks of machinery, as personal requirements for corrective maintenance becomes unnecessary.

That was the case of the gas production site of las Cira-Infantas in Colombia, where the staff requirement to take actions and manually eliminate the gas locking effect in pumps was reduced to zero, as the downtimes due to this effect were eliminated (Chira et al., 2017).

Extended life of equipment
Reducing the wear and tear at the driven system prolongs the lifetime of the motor and equipment. Although is difficult to estimate, earlier replacement of the equipment can be avoided, preventing a loss of extra capital during the lifetime of the machinery (Shakweh, 2007).

Regarding the motor, it has been proved that for every decrease of 10°C in the motor winding temperature achieved through the reduction of the load speed and/or the soft start feature of the VFD, the lifetime of the motor can approximately be doubled (Lawrence & Heron, 2016).

Improved temperature control
In refrigeration or heating applications, the use of VFD's bring a more accurate temperature control than traditional methods. In refrigeration applications for instance, the cold delivered typically have constant running fans which do not have any type of feedback to regulate different supplying zones. With VFD's, sensors can be used to regulate the flow at the supplying zones depending on the specific requirements (Morton & McDevitt, 2000). Because of the better temperature control, cooling and heating requirements and wastes can be reduced compared to a fixed speed system.

5.3. Waste

Reduced water losses and bills

In pump systems, the accurate control of VFD's can reduce the high pressures related to fixed speed systems. As stated by Darweesh (2018), many of the problems producing leakages and occurring in water supply networks are directly related to operating pressures.

Moreover, hydraulic transients associated with fixed speed pumps can be minimized with the use of VFD's. These transients can produce extra leakages as sudden changes in speed and pressures potentially damage the distribution system (Darweesh, 2018).

In the study case carried out by Darweesh (2018), a reduction in approximately 21% of water leakages was achieved by the implementation of frequency drives. Nevertheless, the magnitude of leakage reductions accomplished by the implementation of VFD's differ from network to network, depending on the system characteristics

5.4. Emissions and environment

Reduced GHG emissions

The electricity savings derived from the use of VFD's represent a direct reduction in CO_2 emissions if the electricity is generated on site, or an indirect reduction if the electricity is bought from the grid. Multiple researches have reported the CO_2 reductions achieved by the implementation of VFD's. (Faccio & Gamberi, 2017; Miller, Olateju, & Kumar, 2012; Saidur, 2010). The reduction in emission strongly depends in the emission factors of the specific location where the implementation of VFD's is taking place.

Reduced costs of environmental compliance

In some specific cases, companies could benefit directly from the reduction in CO_2 emissions. If an electricity generation plant is retrofitting a system with a VFD, and this plant has to complain with a CO_2 cap imposed by an emission trading system (ETS), the CO_2 allowances avoided could be sold in the ETS market.

In some other instances, where industries do not produce their own electricity and are not directly benefited from the reduction of emissions, they could benefit from the incentives offered by electricity utility companies, which oftentimes offer rebates or subsidies when a reduction in consumed electricity is achieved by an energy efficiency project (Durocher & Magallon, 2017).

5.5. Work environment

Reduced Noise

It has been demonstrated that VFD's lead to a reduction in the noise power from the motor and driven equipment by reducing the speed (Wang, Astfalck, & Lai, 2002). The reduction of sound levels by varying the speed depends on the switching frequencies of the VFD. These switching frequencies are the rate at which the VFD switches on and off the DC-bus during the PWM process. Higher reductions of noise can be achieved at increased switching frequencies, especially below the base frequency (50 Hz or 60 Hz) (ABB, 1996).

The elimination of throttles for the flow of control also reduces the level of noise generated by the system (Schmager, Mannistö, & Wikström, 2007). Moreover, the soft start capabilities of VFD's allow the speed of the pumps or fans to be ramped up to the required capacity and eliminate the start-up noise (Cohen, 2007).

Different companies have reported the noise reductions brought by VFD's. In the Metropolitan Waterworks Authority in Bangkok for example, a reduction of approximately 10-15 dB was achieved after implementing drives at their water distribution pumping stations (ABB, 2006).

It has been shown that VFD's also contribute to noise, however it can be avoided by verifying the excitation of any natural frequency or harmonic over the full speed range of operation. These critical frequencies increase vibration and produce abnormal noise in the driven equipment. If a critical frequency is found, they can be programmed as a "skip" frequency on the drive and prevent the operation of these specific speeds (ABB, 1996). Further harmonic mitigation methods such as passive and active filters can be used to prevent the electromagnetic noise caused from harmonics introduced by VFD's (Lo et al., 2000)

Because every motor, pump or fan reacts differently in respect to the acoustical noise produced by a particular VFD output waveform, and because there are no common procedures or international standards available to evaluate the sound power of a variable speed systems, it is not possible to accurately determine the noise level reduction in any particular application (Wang et al., 2002).

A reduction in the noise levels enhances a greater comfort and reduces the risk of accident and occupational disease. Moreover, it can help to meet stringent noise regulations (EATON, 2015).

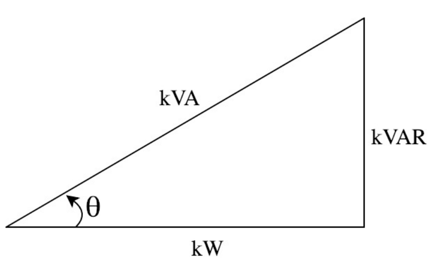
Improved worker/installation safety

Additionally to the benefits that drives can bring to personnel hearing by the noise reduction, VFD's can enhance workers and installation safety by reducing the need of labour work due to operation and maintenance services (Arif & Humayun, 2016).

Improved temperature control (thermal comfort)

As mentioned before, VFD's provide a better temperature control. A better thermal comfort can be realized if drives are installed in HVAC applications at industry facilities. Although comfort cannot be quantified in an objective manner, studies have reported a reduction in staff complaints due thermal discomfort, after the implementation of drives in central air processing units (ADEME, 2011).

5.6. Other



$$PF = \cos\theta = kW/KVA$$

Figure 7. PF in sine wave power

Improved power quality

Motors are inductive loads that require working power (kW) to perform the actual work, and reactive power (kVAR) to sustain the magnetic field that keeps the rotation. Working power is the real power being consumed by the motor. Reactive power in the other hand doesn't perform useful work, but circulates between the generator and the load, and places a drain in the power source and the distribution system. Both active and reactive power make the apparent power (kVA) (See Fig. 7). (EATON, 2014)

Power factor (PF) is defined as the ratio between real or active power to total apparent power and it is an indicator that shows how effectively the power is being used by loads. The closer this ratio is to unity, the better the electricity utilization is. Normally, energy suppliers charge large industrial customers with high penalties when their PF is low because of the needed relocation of real and reactive power within the system. (Rucinski, 2013)

Comparing to other types of loads, induction motors have relatively lower power factors, especially when the motor is oversized, as they draw high reactive currents to support the magnetic fields that cause their rotation (Carrier Corporation, 2005).

Due to the rectification from AC to DC in the rectifier section and the capacitors located at the DC bus, VFD's provide a constant power factor near unity regardless the power factor of the load machine and the controller installation (EATON, 2014).

Nevertheless, since each VFD and motor have their own specific power factor characteristics depending on their construction, it is difficult to develop a method for evaluating the improvements in power factor for all applications. (Jarc & Connors, 1985).

Elimination of additional equipment parts

VFD's eliminate the need of mechanical control devices such as dampers, valves and electronic parts such as sensors used to regulate flow rates. Additionally, the use of VFD's can eliminate the need of capacitors used to improve the power factor of a motor (Peltola & ABB, n.d.; Sylwester et al., 2016).

5.7. Drawbacks

Harmonics

The main disadvantage brought by the use of a VFD is the effect of harmonics injected into the power system. Harmonics are introduced into the electrical system by non-linear loads such as VFD's, which deviate the nearly pure sinusoidal voltage and current wave coming from the electrical power supply utility (Nau & Mello, 2000).

Harmonics pollute the electrical network and bring negative effects to its connected equipment if the distortion increases above certain limit (ABB, 2017). They can overheat motors, generators, transformers and conductors connected to the same power supply as the devices generating the harmonics. Harmonics can lead to an increase in process interruptions and incurring in higher operating costs (Saidur et al., 2012). Furthermore, harmonics can cause false readings in sensitive devices such as meters, flickers in electronic displays and lighting, and trips in circuit breakers (Saidur et al., 2012).

Limits for harmonic distortion are given by national and international standards organizations. Additionally, many transmission and distribution system operators have their own regulations for harmonic limits introduced into the power system, which can incur in penalties in case of violation (A.T. De Almeida et al., 2003a).

Nowadays different types of methods to reduce the introduction of harmonics by VFD's exist, including passive and active filters, line reactors, different electrical topologies and low harmonic VFD's (ABB, 2017; Carrier Corporation, 2005).

The MTE corp Matrix® AP passive filter for instance, virtually eliminates harmonic distortion by adapting to varying power loads (Carrier Corporation, 2005). On the other hand, ABB has introduced its line of ultra-low harmonic drives, which includes an active supply unit and an integrated low harmonic line filter that reduces the harmonic content by up to a 97% compared to a conventional drive unit. The THD of these ABB VFD's is typically 3%; lower than the typical 5-10% THD of passive filters (ABB, 2017). Furthermore, Swamy (2017) proposed different type of topologies and topics to reduce the harmonics distortion. Among them, he proposes a holistic approach of distributing VFD's into different feeders with a delta wye transformer. This approach has been experimentally proven to substantially reduce the introduction of harmonics.

The equipment cost for all required components of a drive system with harmonic reduction solution is estimated to be around 190% compared to the cost of a single drive installation, for both a drive equipped with a passive filter and a low harmonic drive. These two solutions reduce the harmonic content at nominal loads up to less than 10% and 5% respectively. On the other hand, a drive equipped with an active filter represents around the 230% of the cost compared to a single drive installation and limits the harmonic content up to less than 5% at nominal loads. (ABB, 2017).

Operation and maintenance

Although the introduction of VFD's add new elements to maintenance, requiring specialized staff, well-designed VFD system have proved to be reliable enough to not require any major component replacement within the first 10 years of their lifetime (Scheuer et al., 2007). The maintenance schedules reduce to yearly checks to minor components such as air filters, in air-cooled VFD's, and back-up batteries in water-cooled VFD's, therefore making the operation and maintenance costs virtually inexistent (Scheuer et al., 2007). It is also important to mention that most of the checks required for the maintenance of a drive do not require the process shutdown, as they can be made under the operation of a process.

It has been estimated that while a throttling system maintenance service costs around $40 USD, the cost of a maintenance service of an AC VFD costs around $5 USD (ABB, 2011).

Heat rejection and additional space

VFD's generate heat as they operate at efficiencies lower than 100% (Ehrlich, 2015). The heat generation depends in the circuit voltage, the configuration, the power level, and the local environment characteristics (Lawrence & Heron, 2016). In most of the cases, manufacturers are able to provide fan-cooling solutions which do not increase the price of the equipment in a considerable way. Only in very specific applications, water-cooling solutions are required. (Shakweh, 2007)

The size of the area needed for the installation of a VFD depends in the configuration of the system, the power level and the heat rejection required from the VFD equipment. Typically, enclosed VFD's require an area from 228.6x50.8x38.1 cm. (H.xW.xD.) for the smallest power levels to 228.6x88.9x50.8 cm. (H.xW.xD.) for the highest LV power levels. Nevertheless, manufacturers can offer different solutions to meet restricted available spaces. (Lawrence & Heron, 2016).

In addition to the technical drawbacks mentioned before, VFD's face different barriers that have hampered the optimal rate of their adoption at the industry. Among these barriers, low priority for energy efficiency, low visibility of the benefits of VFD's, lack of information and initiative, high transaction costs and/or organizational structure have been found to be most relevant ones (A.T. De Almeida et al., 2003; Fleiter & Eichhammer, 2011).

Although VFD's present already low payback periods usually of 1 or 2 years because of the high energy savings, companies often favour core business projects rather than VFD's, as their purchasing, installation and maintenance processes are perceived as too much time and effort consuming (A.T. De Almeida et al., 2003a).

RQ1 was answered by providing the previous descriptive list of NEB's brought by the use of VFD's in both pump and fan applications. This step helped to further analyse the benefits in the next chapters.

Chapter 6. Quantification of NEB's (SQ2)

In this chapter, the feasibility of quantification and/or monetization of the benefits identified in Phase 1 was assessed. This analysis was focused in methods to quantify the benefits applicable to all pump and fan applications, and not as per case specific.

As stated before, the EB's need to be calculated first in order to have a benchmark and determine how the NEB's can increase the profitability of VFD projects. Therefore, the next subchapters are organized as follows. First, the methods to quantify EB's are presented. Then, the methods to quantify the NEB's as an ex-post are presented. Thereafter, a table summarizing the quantification character of the NEB's is shown. Lastly, examples on how to quantify case specific, ex-post NEB's are given.

6.1. Quantification of EB's

To calculate the energy savings, literature was reviewed in order to find an accurate methods to estimate the energy savings in pump and fan applications fitted with VFD's. To find the energy savings, the current and future situation, before and after the implementation of the VFD had to be analysed.

For the current situation, throttling was used as the reference control method to obtain the energy savings brought by VFD's. Throttling is the traditional and most used control method used in pump and fan flows regulation (Holmes, 1982). The energy savings per year were thus calculated as:

Equation 5. Energy savings per year.

$$E_{sav,yr} = E_{throttle,yr} - E_{VFD,yr}$$

Equation 6. Energy consumption per year, throttle control method.

$$E_{throttle,yr} = \left[\sum_{i=1\%}^{100\%} \left(\frac{P_{p/f,o,i} \cdot h_i}{\eta_{m,i} \cdot \eta_{p/f,i}}\right)\right] \cdot n$$

Equation 7. Energy consumption per year, VFD control method

$$E_{VFD,yr} = \left[\sum_{i=1\%}^{100\%} \left(\frac{P_{p/f,o,i} \cdot h_i}{\eta_{VFD} \cdot \eta_{m,i} \cdot \eta_{p/f,i}}\right)\right] \cdot n$$

Where:
i = percentage of nominal flow
$P_{p/f,o,I}$ = pump or fan output power at flow percentage i (kWh)
h_i = number of operational hours per day at flow percentage i
η_{VFD} = efficiency of the VFD at flow percentage i
η_m = efficiency of the motor at flow percentage i
$\eta_{p/f}$ = efficiency of the pump or fan at flow percentage i
n = number of operational days per year

In pump applications, the hydraulic power can be calculated as (Gülich, 2014):

Equation 8. Pump power output at flow i

$$P_{p,o,i} = \frac{Q_i \cdot \rho \cdot g \cdot H_i}{3.6x10^6}$$

Where:
Q= flow at percentage flow i (m^3/h)
ρ = density of the fluid (kg/m^3)
g = gravity (9.81 m/s^2)
H_i = head at flow percentage i (m)

In fan applications:

Equation 9. Fan power output at flow i

$$P_{f,o,i} = Q_i \cdot \Delta P_i$$

Where:
Q= air flow at percentage flow i (m^3/s)
ΔP = pressure differential at flow percentage i (Pa, N/m^2)

In throttled pumps and fans, the flow is reduced by increasing the losses in the system while closing a valve. This relation between head and flow is represented by their characteristic curve (See Fig. 8[a]). These curves vary from equipment to equipment and are provided by the manufacturers and measured on a test by throttling the discharge valve rate (Gulich, 2014).

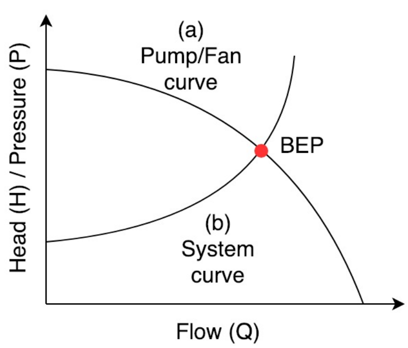


Figure 8. Q-H/P curve representative of a centrifugal pump or fan.

In order to estimate the curve of the equipment and determine the specific head or pressure at any flow, the use of the maximum head/pressure value can be used. This value is usually shown in the nameplate of the pump or specified in the equipment characteristic curve provided by the manufacturer and indicates the head/pressure generated by the pump/fan at full speed and zero flow.

The characteristic equation of a performance curve can be described as:

Equation 10. Characteristic equation of a pump or fan.

$$H_i/\Delta P_i = a + bQ_i + c{Q_i}^2$$

With a very reasonable representation by (Carlson & Member, 2000):

Equation 11. Characteristic equation of a pump (simplified).

$$H_i/\Delta P_i = a + c{Q_i}^2$$

Where:
a = maximum head
b and c = coefficients characteristic of the pump or fan curve

By using the two points available from the curve (one determined from the nominal head/pressure and nominal flow at the BEP, and the other determined with the maximum head/pressure at zero flow), a system of two variables and two equations can be solved to obtain the values of *a* and *c.* The characteristic equation can be used to calculate the head/pressure, and consequently the power at any flow by Eq. 8 or Eq. 9.

With VFD control, the head and power vary with the flow according to the affinity laws (See Fig. 8[b]). The power required by the pump or fan at any varying flow was therefore calculated by Eq. 1.

To monetize the energy savings the following formula was used:

Equation 12. Energy cost savings per year.

$$C_{Esav,yr} = E_{sav,yr} \cdot C_{elec}$$

Where:
$C_{sav,yr}$ = electricity cost savings per year (€)
C_{elec} = electricity price of a specific location (€/kWh)

6.1.1. Efficiency of pumps/fans

The affinity laws are used to describe the pumps and fans behaviour when the speed is variated. These laws assume that the efficiencies of the equipment are kept constant at any point of the system curve (i.e. different flows). Yet, the calculation of efficiencies through the affinity laws are just approximations which do not consider factors that do not scale with velocity and that depend on the machine size (Simpson, Asce, & Marchi, 2013).

As a result, the equation proposed by Sarbu & Borza (1998) was used to calculate the efficiency of the pumps and fans at reduced speeds (See Eq. 13). This equation has been proved to decrease the error in the efficiencies estimations compared to measured values (Marchi, Simpson, & Ertugrul, 2012).

Equation 13. Pump/fans efficiency at partial flows

$$\eta_{p/f,i} = 1 - (1 - \eta_{p/f}) \cdot \left(\frac{Q}{Q_i}\right)^{.1}$$

Where:
$\eta_{p/f,i}$ = efficiency at flow i
$\eta_{p/f}$ = nominal pump/fan efficiency
Q = nominal pump/fan flow
Q_i = flow at percentage flow i

The nominal efficiencies of pumps and fans are usually indicated in the nameplate. Nevertheless, they are only valid at the pump BEP values of head/pressure and flow. The efficiencies curve at different flows is derived from tests and provided by the manufacturer (Carlson & Member, 2000). Therefore, the efficiencies at various flows while throttling were assumed to be the same as the efficiencies calculated for VFD's at different flows through Eq. 13.

6.1.2. Efficiency of Motors

The efficiency of the motors depends in the manufacturer, their design characteristics, the size, the load and the speed of the driven load. Although the motor efficiencies are usually obtained from the nameplate, they are only accurate under rated loads and speeds (Li, Liu, Lau, & Zhang, 2015). These rated efficiencies are usually high, however it has been shown that approximately half of the industrial motors are loaded below 40% of its rated capacity (Mulobe & Huan, 2012).

To obtain efficiencies at partial loads, generic curves are commonly used. Nevertheless, this curves are not valid at partial speeds. Li et al. (2015) proposed a novel and accurate method to calculate the efficiency of motors at partial load and partial speeds with a relatively low error compared to efficiencies obtained by experimental tests. In this non-intrusive method, the efficiency at partial loads and speeds of different flow rates is given by the equation:

Equation 14. Efficiency at partial loads and speeds (size motors > 4kW).

$$\eta_{m,i} = \left[1 - (1 - \eta_{m,rated}) \cdot \left(\frac{0.3}{\alpha \cdot \overline{\omega}} + 0.7 \cdot \alpha \cdot \overline{\omega}\right)\right] \cdot 100\%$$

Where:

$\eta_{m,rated}$ = *rated efficiency of the motor*

α = *load ratio*

$\overline{\omega}$ = *speed ratio*

Equation 15. Load ratio.

$$\propto = \frac{w_o}{w_{rated}} = \frac{P_{p/f,j}}{w_{rated}} = \frac{\frac{P_{p/f,o}}{\eta_{p/f,i}}}{w_{rated}}$$

w_o = *actual motor output power*

$P_{p/f,j}$, = *actual pump/fan input power)*

w_{rated} = *rated motor output power*

Equation 16. Speed ratio.

$$\overline{\omega} = \frac{Q_i}{Q}$$

For size motors equal or smaller than 4kW, and to reduce the relative error of the calculations compared to experimental tests, the motor efficiency can be calculated by a corrected version of Eq. 14 (Li et al., 2015):

Equation 17. Efficiency at partial loads and speeds (size motors ≤4kW.

$$\eta_{m,i} = \left[1 - (1 - \eta_{m,rated}) \cdot \left(\frac{0.4}{\alpha \cdot \overline{\omega}} + 0.6 \cdot \alpha \cdot \overline{\omega}\right)\right] \cdot 100\%$$

6.1.3. Efficiency of the VFD's

The efficiency of VFD's depends on their rated power, load, manufacturer and varies from installation to installation depending on the system characteristics (Marchi et al., 2012). Nevertheless, the values representative of a typical PWM VFD performance differ in a very small proportion even at loads of 42% (U.S. Department of Energy, 2012).

For the sake of simplicity and because the lack of theoretical methods to calculate the efficiency of VFD's at different loads and speeds, a conservative value of 95% was used for the calculation of energy savings. This assumption is sustained by the findings in the study by Burt, Piao, Gaudi, Busch, & Taufik (2008) where the efficiencies of VFD's were tested with different motors and found to not fall below 95% even at load factors lower than 30% and speeds of 40% from their rated values.

6.2. Quantification of NEB's

Data was reviewed using the database Scopus to search for feasible methods to quantify the NEB's in an ex-ante evaluation. The benefits described in the following subchapters were found to be quantifiable and/or monetizable as an ex-ante and applicable to all pump/fan applications.

6.2.1. Reduced GHG emissions

To calculate the reduction in CO2 emissions brought by the electricity savings, the following formula was used:

Equation 18. CO_2 savings per year.

$$CO_{2,sav,yr} = E_{sav,yr} \cdot EF$$

Where:
EF = Emission factor (CO_2/kWh)

The emission factors can be either calculated or obtained by different sources, accordingly to the electricity production generation mix of a particular location. In this case, the national average emission factors, in CO_2 per electricity consumed, were obtained through the "CoM Default Emission Factors for the Member States of the European Union" (2018) report.

In case a particular industry benefits directly for the emission reductions (i.e. they are power plants implementing VFD's, or the industries generate their own electricity on site), and the investor is able to sell the CO_2 permits in an emission trading system (ETS), the formula to estimate their cost benefits is:

Equation 19. CO_2 cost savings per year.

$$C_{CO2,sav,yr} = CO_{2,sav,yr} \cdot C_{CO2,allow}$$

Where:
$C_{CO2,allow}$ = Cost of CO_2 emission allowances in a particular ETS (€)

6.2.2. Extended equipment life

While the extension in life expectancy of the driven equipment is hard to quantify due to the interaction of multiple factors influencing it, the effect of varying the load in the lifetime expectancy of the motors can be generalized and better estimated for every application.

The two main reasons causing squirrel cage induction motors to fail are the deterioration of the insulation materials and the bearing fatigue damage (De Abreu & Emanuel, 2002).

The bearing fatigue is the only cause of failure if the bearings are properly lubricated. The estimation of bearing lifetime due to fatigue is however a complex calculation as it depends on different parameters such as the number of balls, ball diameter, the radial and axial loads of the bearings and type of bearings (Baumeister & Avallone, 1999).

Nevertheless, Brancato (1992) proposed a method to estimate the lifetime of the insulation system of a motor according to its percentage of load (See Eq. 20). This method is derived from the Arrhenius chemical rate equation which is used to determine the life aging of an insulation system.

Equation 20. Life estimation of insulation systems of motors at partial loads.

$$L_x = L_{100} \cdot 2\, exp\left[\frac{T_c - T_x}{HIC}\right]$$

Where:
L_x = percentage of lifetime at partial load (%)
L_{100} = percentage of lifetime at rated load (100%)
T_c = total allowable temperature for an insulation class (℃)
T_x = hot-spot temperature for an insulation class (℃)
HIC = halving interval for an insulation class (℃)

The total designated temperature rises (T_c) and the halving interval (HIC) for the different insulation classes based on 20,000 hours lifetime expectancy at 100% and a motor service factor of 1 are found in Table 2. For service factors higher than 1, the load has to be corrected by the value of the motor service factor. A motor operating at rated load and having a service factor of 1.25 for example, may be considered as operating at 75% load (Brancato, 1992).

Table 2. Total allowable temperature, halving intervals and total allowable temperature rise for motor insulation classes

Insulation system	T_c	HIC	ΔT
Class A	105 °C	14 °C	65 °C
Class B	130 °C	11 °C	90 °C
Class F	155 °C	9.3 °C	115 °C
Class H	180 °C	8 °C	140 °C
Class H220	220 °C	10 °C	180 °C

The hot-spot temperatures (T_x) for an insulation class can be calculated as:

Equation 21. Hot-spot temperatures.

$$T_x = F \cdot \Delta T + 40$$

Where:
F = rated loss factor
ΔT = allowable temperature rise (°C)

The rated loss factor *(F)* for partial loads are shown in Table 3. These values represent the percentage of motor rated life loss at a specific load and were derived from a generalized losses versus load curves (Brancato, 1992). The allowable temperature rise values *(ΔT)* for an ambient temperature of 40°C and a service factor of 1 are shown in Table 2. For ambient temperature other than 40°C, and in case the temperature profile is available, the calculations would need to be done as specified per Brancato (1992) study.

Table 3. Rated life loss factor at various loads.

% load	% loss factor F
100	100
90	88
75	77
50	53

The average load for obtaining the *(F)* value was calculated from the operation schedule in both control schemes. For load values not found in Table 3, the rated loss factor was then interpolated or extrapolated in Excel using a third-degree polynomial trend line from the available data.

In order to determine the total increase in lifetime expectancy between the throttle and VFD control methods, the difference in increase of lifetimes due to the reduction of loads by the use of throttles and VFD's was obtained ($L_{x,net} = L_{x,VFD} - L_{x,throttle}$).

This increase in lifetime expectancy did not however take into account the times the motor starts and stops. For this calculation, the number of starts/stops of the motor on a time basis would have to be known. Brancato (1992) estimated that for every motor start, the calculated life expectancy reduces by one hour. The soft start capability of the VFD's would then increase the lifetime of the motor even more comparing to the throttle control method, as this feature limits the high inrush currents drawn by the motor at the start and extends the lifetime of the insulation.

The monetization of the lifetime expectancy increase needed to be analysed having into account the lifetime of the project and the operating profile. To calculate the number of hours on a project lifetime basis, the number of operating hours per year was multiplied per the assumed number of years of the project. This resulted in the total operating hours per project.

As stated before, both control methods result in an increase in the lifetime expectancy of the motors by decreasing the load. A cost benefit is only realized when the lifetime expectancy of the motor brought by throttles is lower than the total operational hours in the project life, and the increase in expectancy by the VFD is higher than this value. For instance, if the expected lifetime of the motor by using throttles is 10,000 hours, but the total operational hours in the project is 8,000 hours, no replacement of the motor is required during the lifetime of the project. In the other hand, if the expected lifetime of the motor by using throttles is 10,000 hours, and the total operation hours during the project lifetime is 15,000 hours, an extra motor replacement would be required if the lifetime expected with a VFD is higher than the 15,000 hours.

Once the number of extra motors was determined, the avoided capital loss was calculated by multiplying the number of extra motors required during the lifetime of the project times the cost of the motor (Eq. 22).

Equation 22. Avoided capital loss due to extended lifetime of the motor

$$C_{Motsav,yr} = \frac{\#motors_{repl} \cdot C_{motor}}{T}$$

Where:
$C_{motsav,yr}$= avoided capital loss per year due to extended lifetime of the motor (€)
$\#motors_{repl}$ = number of extra motor replacements required
C_{motor} = cost of the motor (€)
T = lifetime of the project (years)

6.3. Quantification character of NEB's

Table 4 summarizes the quantification character of the NEB's identified in the previous chapters. It develops from Cooremans' list and categorizes the benefits as per quantifiable (Q) or non-quantifiable (NQ), and as per ex-ante (E-A) or ex-post (E-P) if they can be quantified either prior or after the implementation of the equipment.

Table 4. Summary of the quantification character of the NEB's

Category	NEB	Quantifiable/Non-quantifiable	Ex-ante/Ex-post
Production	Improved process control	Q	E-P
	Improved product quality/consistency	Q	E-P
	Improved production reliability	Q	E-P
	Increased productivity	Q	E-P
	Improved equipment performance	Q	E-P
	Improved flexibility of production	Q	E-P
	Shorter production cycles (shorter process cycle times)	Q	E-P
	Increased product yields	Q	E-P
Operations and maint.	Reduced wear and tear on equipment and machinery	Q	E-P
	Reduction in operation and maintenance costs	Q	E-P
	Extended life of equipment	Q	E-A/E-P*
	Reduced malfunction or breakdown of machinery and equipment (downtimes)	Q	E-P
	Reduction in labour requirements	Q	E-P
	Improved temperature control	Q	E-P
Waste	Reduced water losses and bills	Q	E-P
	Reduced waste heat	Q	E-P
Emissions/environment	Reduced GHG emissions	Q	E-A
	Reduced costs of environmental compliance	Q	E-A
Work environment	Reduced noise (auditive comfort)	NQ	
	Improved worker/installation safety	Q	E-P
	Improved temperature control (thermal comfort)	NQ	
Other	Elimination of additional equipment parts	Q	E-P
	Improved power factor	Q	E-P

**For the extension of life of the motor E-A applies. For the extension of life of the pump/fan E-P does.*

6.4. Quantification of ex-post NEB's

Cooremans, (2017) provides examples of indicators to measure the NEB's listed in her categorization. These indicators enable an easier quantification of the benefits. Two examples using Cooremans' indicators are given below to show how the quantification of ex-post NEB's can be done.

I. For the NEB "Improved product quality /consistency" the number of defects needs to be measured prior and after the retrofit. The cost of each scrapped unit can be determined and multiplied by the reduction of defects to further monetize the savings in any time basis.

II. In the case of the NEB "Reduced malfunction or breakdown of machinery and equipment", the number of breakdowns due to malfunction of machinery before and after the implementation of the VFD need to be measured. The cost incurrence of each downtime can be then evaluated to monetize such benefit.

It is important to mention that for the quantification of the ex-post benefits, a characterization of the system prior the retrofit is needed to benchmark the benefits after the implementation phase. If for instance, for the previous examples, the number of downtimes or defect units are not recorded before the installation of the VFD, the quantification of the benefits will not be possible.

Chapter 7. Study case (SQ2)

A theoretical (i.e. fictive) study case is presented to show how the quantification of NEB's can impact the profitability of a VFD energy efficiency project.

In this study case, a Dutch gas power plant retrofits the condenser water-cooling system of the plant. Currently, the flow of water is throttled by an electro valve at a 100% flow during peak hours and a 70% of the maximum flow during non-peak hours. The pumps peak hours are 6 hours per day, whereas the non-peak hours are 18 per day during the 365 days of the year. A single pump is analysed. Table 5 shows the characteristics of the system.

Table 5. System characteristics of study case.

Pump	Lowara Centrifugal Pump 150-400/1100[9]
Flow	510 m³/h
Head	56 m
Max. head	63.9 m
Rated Efficiency	85.5 %
Motor	Siemens GP/SD VSD10 line. Motor 1LE1503-3AB0[10]
# of poles	4
Rated power	110 kW
Rated efficiency	95.4%
Insulation class	Class F
Service factor	1
VFD	
Rated efficiency	95%[11]
System	
Frequency	50 Hz

The electricity consumption with a throttle and VFD control method is calculated by Eq. 6 and Eq. 7, giving a total electricity consumption of 694.7 MWh and 460.4 MWh respectively. Total energy savings of 234.2 MWh per Eq. 5 are obtained. At an electricity price of 86.3 €/MWh for non-household users in the Netherlands[12], the electricity saving costs total €20,216.2 per year.

By using the Eq. 18 with an emission factor of .429 tCO_2/MWh[13], emissions reduction of 100.5 tonnes of CO_2 per year are realized. This power plant is assumed to benefit directly from the reduction in CO_2 by selling the emission allowances in the European ETS. At a price of 23.50 €/tCO_2[14], annual savings of €2,361.63 are achieved.

The increase in the lifetime expectancy of the motor in both control methods can be estimated by using Eq. 20. The increase in lifetime by fitting the pump with a VFD is of 2,000,000 hours, considering a reference lifetime of 20,000 hours running at full load. By using a throttle, the increase in lifetime is of 320,000 hours.

[9] (Lowara-Lenntech, 2016)
[10] (Siemens, 2018)
[11] Assumed efficiency value as per described in Chapter 6.1.3.
[12] Electricity price as per first semester of 2018 (EUROSTAT, 2018)
[13] Emission factor as of 2013 (Koffi et al., 2017)
[14] CO_2 allowance price as per February 7th, 2019 (EEX, 2019)

Assuming an average lifetime of the VFD equipment of 10 years (Miller et al., 2012), 87,600 operational hours are required during the lifetime of the project. In this case a cost benefit is not realized because the increase in lifetime brought by throttles already exceeds the total operational time of the project.

Considering a total initial investment cost of €18,600.00 (A.T. De Almeida et al., 2003a), a discount rate of 10%, and using Eq. 2 and Eq. 3 the profitability of NEB's can be assessed. Table 6 shows the difference in PBP, NPV and IRR that can be achieved by considering only the EB's and the EB's together with the NEB's.

Table 6. Profitability potential results.

Indicator	EB's	EB's + NEB's	Difference
PBP (years)	0.92	0.82	0.10
NPV (€)	105,619.0	120,130.2	14,511.2
IRR	109%	121%	13%

Furthermore, the following NEB's are identified to be brought in this application but only quantifiable as an ex-post:

- Improved production reliability
- Improved equipment performance
- Reduced wear and tear on equipment and machinery
- Reduction in operation and maintenance costs
- Reduced malfunction or breakdown of machinery and equipment (downtimes)
- Reduction in labour requirements
- Reduced noise (auditive comfort)
- Elimination of additional equipment parts
- Improved power factor

It is clear that the NEB's will only increase the profitability of an ex-ante evaluation if the user has economic benefits from the emission reductions brought by the electricity savings and/or if the reduced wear and tear in the motor brings a reduction in the number of motors required during the lifetime of the project. Moreover, the degree the ex-ante NEB's have an overall impact on the profitability of a project will be proportional to the EB's magnitude, but inversely proportional to the EB cost savings (i.e. greater EB's costs, lower NEB's profitability potential).

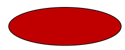
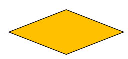
To have a general approximate of the EB's potential of VFD's in the industry, (A.T. De Almeida et al., 2003a) found average electricity savings of 35% for VFD's in general pump and fan applications. For both applications, an applicability of 60% to motor loads in the industry sector was estimated. From this applicability percentage, a 9% and 7% was found to be the value of VFD's already applied, resulting in a 51% and 53% of technical potential for pump and fan applications, respectively. The paper and carboard, the basic chemistry and the iron and steel are the industries with largest percentage of motors in which the application of a VFD is cost-effective.

As mentioned before and seen by the study case, the PBP from only accounting the EB's in VFD's projects already presents sufficient economic arguments for their implementation.

Chapter 8. Calculation method (SQ3)

In this chapter, the calculation method used in the study case to estimate the technical and economic potential of NEB's in a VFD project is presented. This method includes the quantification of both EB's and NEB's and is graphically represented by the flow chart shown in Fig. 9. The symbols used in this flow chart are described in Table 7. The flow chart together with the table are largely self-explanatory.

Table 7. Flow chart symbols description

Symbol	Description
	Start and end of the calculation method
	Required inputs
	Calculation method outputs
	Calculation method process
	Decision inputs

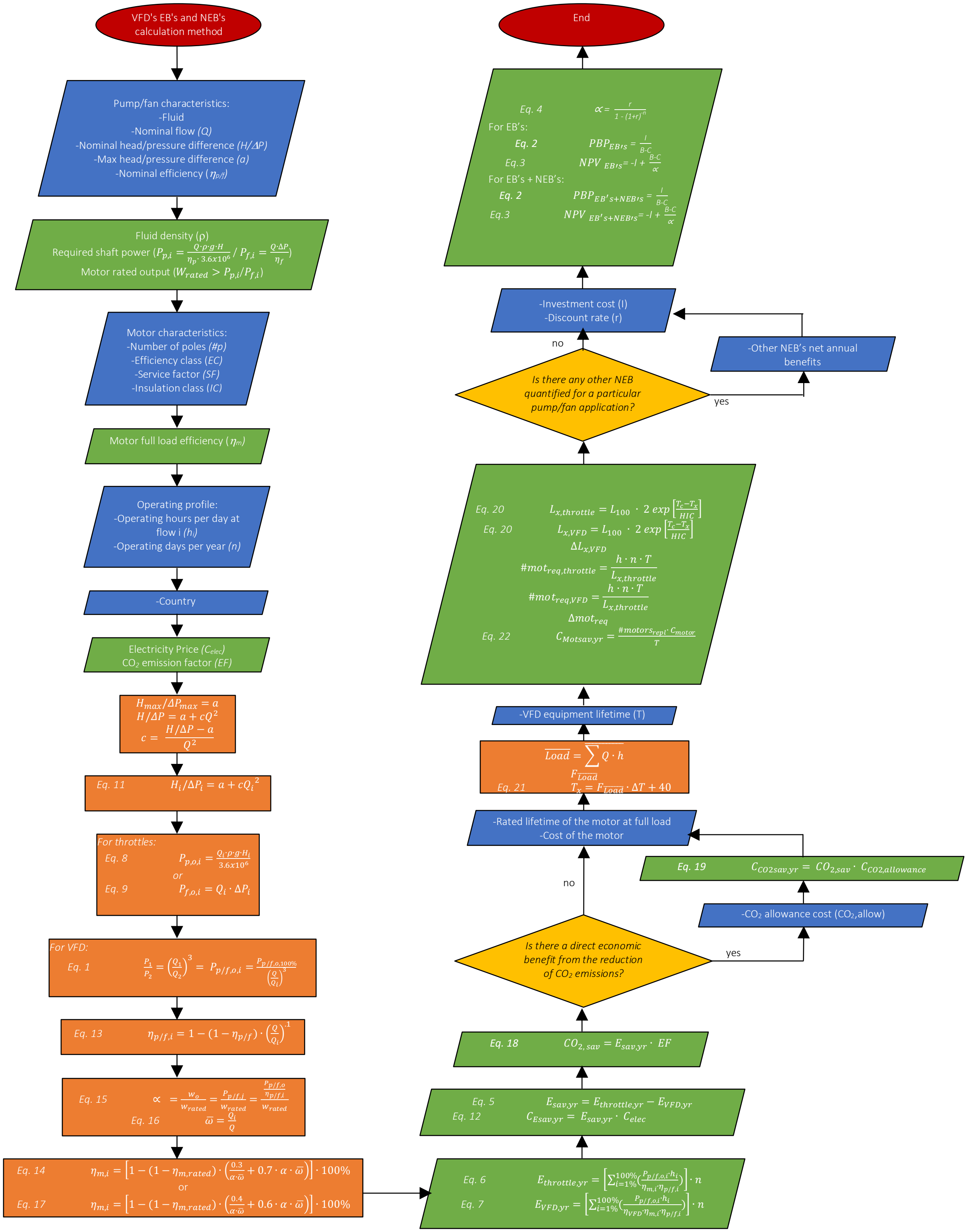


Figure 9. Flow chart depicting the calculation method

Chapter 9. NEB's Model (SQ3)

A spreadsheet-based model compiling the calculation method was developed as an outcome of this thesis. This model assesses the profitability of NEB's and further works as ex-ante tool to estimate the EB's of a VFD energy efficiency project. It provides a degree of flexibility by allowing different input parameters. It consists of two sheets named as "Pumps" and "Fans" depending on the application to evaluate. In this model, the blue cells indicate user inputs, while the green cells indicate the model outputs.

Following the flow chart shown in Fig. 9, the model works as described in the succeeding paragraphs. For the sake of clarity, the description of the model focuses in a pump application, using the terminology related to it, however the same methodology applies for fan applications.

Firstly, the characterization of the pumping characteristics is required from the user (See Table 8). These parameters include the nominal flow, which is the maximum system flow that the pump has to deliver; the nominal head, which is the head that the pump needs to generate to produce the nominal flow considering the system curve; the maximum head developed by the pump at zero flow; the fluid of the pump; and the efficiency of the pump at the nominal flow. Typical density values for water, crude oil and gasoline are provided by the model. Nevertheless, other density values can also be specified instead.

Table 8. Model pump system characteristics

Pump		
Nominal flow	510	m^3/h
Nominal head	56	m
Max head	63.9	m
Fluid	Water	
Fluid density	1000	kg/m^3
Pump efficiency	85.5	%
Required shaft power	90.9	kW

After entering this information, the required shaft power (i.e. pump input power) is calculated to determine the minimum rated power of the motor. The motor power output is selected according to the next commercial motor size available. If a different motor size is required, the value of the size of the motor can be other way specified. Nevertheless, this value cannot be lower than the required shaft power.

Next, other motor parameters need to be characterized (See Table 9). First, the number of motor poles and the efficiency class have to be indicated by the user. The model then determines the motor efficiency at full load according to the international standard IEC 60034-30-1[15]. This standard performs as a minimum performance standard (MEP) in most of developed countries (A.T. De Almeida et al., 2003a) and establishes a set of limit efficiency values based on frequency, number of poles, and motor power. It specifies efficiency classes for single-speed motors that are rated for operation on a sinusoidal voltage supply (i.e. alternate voltage AC). In case the efficiency of the studied motor does not match the efficiency values from the IEC standard, they can be specified otherwise.

[15] The nominal efficiencies of motors were obtained with the standard IEC 60034-30-1 and not with the standard IEC 60034-30-2, as the last considers a harmonic introduction factor to correct the efficiencies in VFD applications. In this case, harmonic introduction due to the implementation of VFD's are assumed to be neglectable as per the different methods stated in the results of Chapter 5.

It should be noted that the model only retrieves efficiencies from the IEC 60034-30-1 standard for LV motor power sizes ranging from 0.75 kW to 375 kW, since these represent the largest proportion of motors in the industry (Faccio & Gamberi, 2017)

Table 9. Motor system characteristics

Motor		
Rated Motor Power	110.0	kW
Motor Poles	4	Poles
Motor Efficiency Class	IE3	
Motor Full Load Efficiency	95.4	%
Service Factor	1	
Motor insulation class	Class A	

For the VFD equipment, only the rated efficiency needs to be specified. A default value of 95% is pre-set as per mentioned in chapter 3.4, however this value can be modified (See Table 10).

Table 10. VFD characteristics

VFD		
VFD Efficiency	95	%

The country of study needs to be selected to determine the electricity price according to EUROSTAT (2018), as per the first semester of 2018, and the EF's as of 2013 according to Koffi et al. (2017). The model allows only European countries to be selected, but other values of electricity prices and EF's can be introduced. (See Table 11).

Table 11. Other parameters selection

Other Parameters		
Country	Netherlands	
Electricity Price	0.086	€/kWh
CO2 Emission Factor	0.429	tCO_2/MWh

Thereafter, the operating schedule to be indicated. This schedule is expressed as a percentage reduction of the nominal flow in number of hours per day. In addition, the number of operating days per year must be specified. The model then calculates the total operation hours and the capacity factor per year (See Table 12)

Table 12. Operating profile characteristics

Operating profile										
Flow rate	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Operation hours per day	0	0	0	0	0	0	18	0	0	6
Total operation hours per day	24									
Operation days per year:	365									
Total operation hours per year	8760									
Annual capacity factor	100%									

After specifying this information, the model calculates the energy consumptions for both throttling and VFD's control methods and calculates the annual energy savings and their cost benefits. (See Table 13).

Table 13. Annual energy consumptions and savings

Energy benefits		
Energy Usage without VFD	694.7	MWh
Energy Usage with VFD	460.4	MWh
Energy Savings per year	234.3	MWh
Energy Saving costs per year	20,216.1	€

These energy savings are then used to calculate the annual reduction in CO_2 emissions. If a user benefits directly from the reduction of CO_2 emissions, the cost of the CO_2 allowances can be indicated in order to estimate the CO_2 cost benefits. (See Table 14)

Table 14. Reduction of GHG NEB

Non-energy benefits		
CO_2 emissions reduction per year	100.49	tCO2
CO_2 allowance cost (ETS)	23.5	€/tCO_2
CO_2 direct cost benefits per year	2361.6	€

Thereafter, the user must specify the estimated lifetime expectancy of the motor at full load, the VFD, as specified by the manufacturer, and the cost of the motor, to calculate the extension in lifetime expectancy and where applicable, the resulting cost benefits. (See Table 15).

Table 15. Extended lifetime of equipment NEB

Rated lifetime of the motor at full load	20,000	hours		
Motor cost	2,000	€		
VFD equipment lifetime	10	years		
Extended lifetime of motor	Throttle	VFD	Difference	
Extended lifetime at reduced load	284	570	286	% of expected lifetime
Extended lifetime at reduced load	56,755	113,983	57,227	hours
Motors required during project lifetime	2	1	1	# of motors
Avoided capital loss per project lifetime	2,000	€		
Avoided capital loss per year	200.0	€		

The model allows the indication of other NEB's realized and quantified by the user for their consideration in the profitability analysis. (See Table 16).

Table 16. Other NEB's quantified by the user

Other NEB's quantified by the user:	Annual benefits	
		€
		€
		€

Lastly, the user specifies the investment required and the discount rate for the implementation of the VFD. The model then calculates capital recovery factor according to the discount rate. (See Table 17).

Table 17. Economic parameters indication

Profitability assessment		
Investment cost	18,600	€
Discount rate	0.10	%
Capital recovery factor	0.16	

After all the above parameters and calculations have been indicated and performed, the model evaluates the profitability of the NEB's by comparing the values of PBP, NPV and IRR indicators by considering only the EB's, to the values obtained considering the EB's together with the NEB's. (See Table 18).

Table 18. Profitability evaluation

Indicator	EB's	EB's + NEB's	Difference	
PBP	0.92	0.82	0.10	
NPV	105,619.0	121,359.1	15,740.1	years
IRR	109%	121%	13%	€

This model serves as a starting point to further evaluate NEB's and the profitability of VFD's efficiency projects. It results to be a great scientific contribution as the lack of transparent methods to quantify benefits is a major barrier for effective policy making and to a more global acceptance of the energy efficiency potential in industrial motor systems (McKane & Hasanbeigi, 2011).

Table 19. Overview of the model

Pump		
Nominal flow	510	m^3/h
Nominal head	56	m
Max head	63.9	m
Fluid	Water	
Fluid density	1000	kg/m^3
Pump efficiency	85.5	%
Required shaft power	90.9	kW
Motor		
Rated Motor Power	110.0	kW
Motor Poles	4	Poles
Motor Efficiency Class	IE3	
Motor Full Load Efficiency	95.4	%
Service Factor	1	
Motor insulation class	Class A	
VFD		
VFD Efficiency	95	%
Other Parameters		
Country	Netherlands	
Electricity Price	0.086	€/kWh
CO2 Emission Factor	0.429	tCO_2/MWh

Operating profile										
Flow rate	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Operation hours per day	0	0	0	0	0	0	18	0	0	6
Total operation hours per day	24									
Operation days per year:	365									
Total operation hours per year	8760									
Annual capacity factor	100%									

Energy benefits		
Energy Usage without VFD	694.7	MWh
Energy Usage with VFD	460.4	MWh
Energy Savings per year	234.3	MWh
Energy Saving costs per year	20,216.1	€
Non-energy benefits		
CO_2 emissions reduction per year	100.49	tCO2
CO_2 allowance cost (ETS)	23.5	€/tCC
CO_2 direct cost benefits per year	2361.6	€

Profitability assessment				
Investment cost	18,600	€		
Discount rate	0.10	%		
Capital recovery factor	0.16			
Indicator	EB's	EB's + NEB's	Difference	
PBP	0.92	0.82	0.10	
NPV	105,619.0	121,359.1	15,740.1	years
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Rated lifetime of the motor at full load	20,000	hours		
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Extended lifetime of motor	Throttle	VFD	Difference	
Extended lifetime at reduced load	284	570	286	% of expected lifetime
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Motors required during project lifetime	2	1	1	# of motors
Avoided capital loss per project lifetime	2,000	€		
Avoided capital loss per year	200.0	€		

Other NEB's quantified by the user:	Annual benefits	
		€
		€
		€

Chapter 10. Discussion

It is important to mention that the non-quantified NEB's presented do not necessarily occur simultaneously in all pump and fan application. A more in-depth analysis of the process is required to determine whether a specific NEB would derive from an individual applications. For example, it may be the case that a process implementing a VFD does not necessarily require a precise control. This would not in turn, lead to a better product quality benefit.

The results of this thesis show that the unpredictability of certain events (e.g. failures of equipment, future productivity requirement) limits the quantification of the NEB's as an ex-ante analysis. In other more favourable cases, it is difficult to quantify these benefits as they require very specific information regarding the system of study. Nevertheless, this research provides sufficient qualitative arguments to realize the potential benefits of VFD's.

10.1. Assumptions

Different assumptions were made to calculate the EB's and NEB's of the theoretical study case. Such was the case of the efficiencies of the driven equipment and of the VFD. These assumptions were based however in literature and considering the most conservative values to not overestimate the benefits.

The results of electricity savings obtained in the proposed study case were compared to the energy saving calculators available online. Different manufacturing companies offer these tools to promote the use of VFD's, however, the tools offered by Siemens and ABB were used to validate the results. In both cases the results were of the same order, with errors of -4.5% compared to ABB and +7% compared to Siemens tools. These errors are attributable to the differences in the efficiencies assumed for the drive, the motor and the driven equipment.

10.2. Sensitivity Analysis

A sensitivity analysis was carried out to test the variability of outputs according to different inputs. The most relevant variables were considered and selected to be examined. The other variables were chosen to be the same as in the study case.

The profitability of the of the NEB "Reduction of GHG emissions" varies directly proportional to the EB's magnitude but inversely proportional to the EB's cost savings. The cost savings brought by the reduction of GHG emissions vary with the EF's and the cost of the CO_2 allowances. The EB's magnitude and cost rely on variables internal to the studied system (e.g. schedule of reduced flow, motor rated power, equipment efficiencies, a characteristics of the pump or fan system) and on the electricity price, respectively. Because the relation of the profitability of this NEB and country specific variables (i.e. EF, cost of CO_2 allowances and cost of electricity) is easier to understand, the sensitivity analysis for the "Reduced GHG emission" NEB was focused on the variables schedule of reduced flow and the motor rated power.

For the variation of the schedule at reduced load, three different scenarios were considered

I. 75% of the time at 70% flow and 25% of the time at 100% flow[16]
II. 75% of the time at 80% flow and 25% of the time at 100% flow
III. 75% of the time at 90% flow and 25% of the time at 100% flow

Fig. 10 shows the average electricity savings for each motor power range and the three load schedules. It is clear that the higher motor powers present the greatest potential of EB's at lower flow reductions (i.e. scenario i). This is explained by the relation of the Affinity laws in terms of flow reductions and power requirements (i.e. lower flow reductions allow higher EB's).

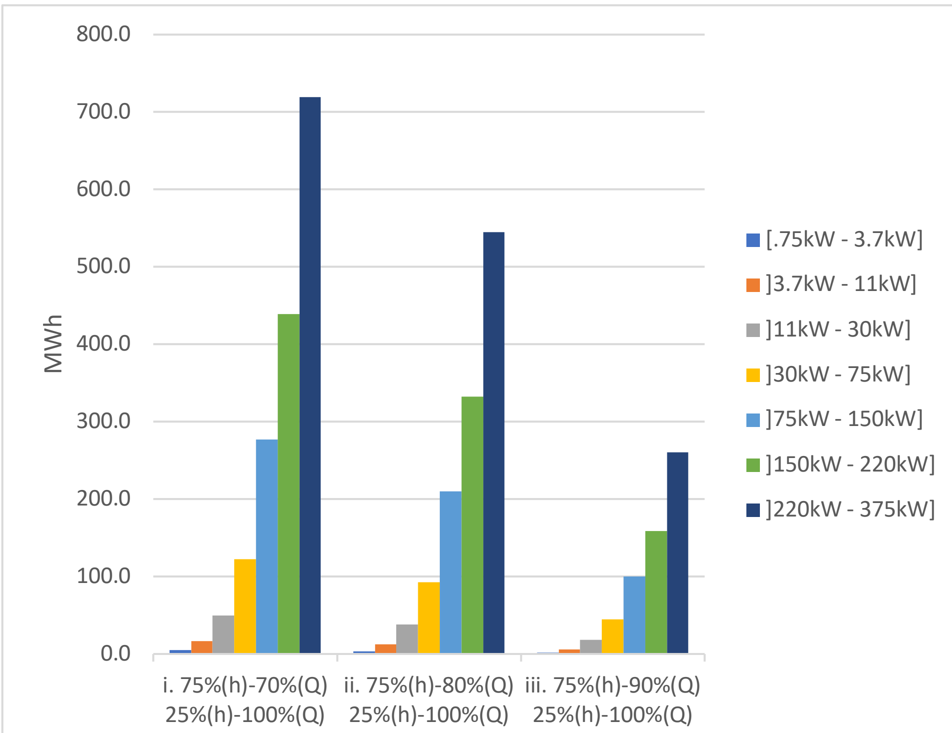

Figure 10. Average annual electricity savings by power range

For the sensitivity analysis of the NEB "Extended lifetime of equipment", the variables chosen to exanimate were the schedule at reduced flow, the motor rated power and the insulation class. The same three previous load scenarios were considered. As mentioned before, all the variables but the ones chosen to be examined in the sensitivity analysis were assumed to be the same as in the presented study case (e.g. lifetime of VFD).

Fig. 11 shows the number of replacement of motors that each of the different insulation classes and the motor power ranges would require during the lifetime of the project. It can be observed that the motor size does not influence the number of motor replacements required. However, lower reduced flows (i.e. scenario iii) and the insulation classes A and B, present the greater potential of economic benefits.

This can be explained by the fact that at higher reduced flows (e.g. scenario i) the extension in lifetime of the motor brought by the throttle already exceeds the total operational hours in the project, so no benefit by the introduction of VFD is realized.

[16] Scenario used in the presented study case

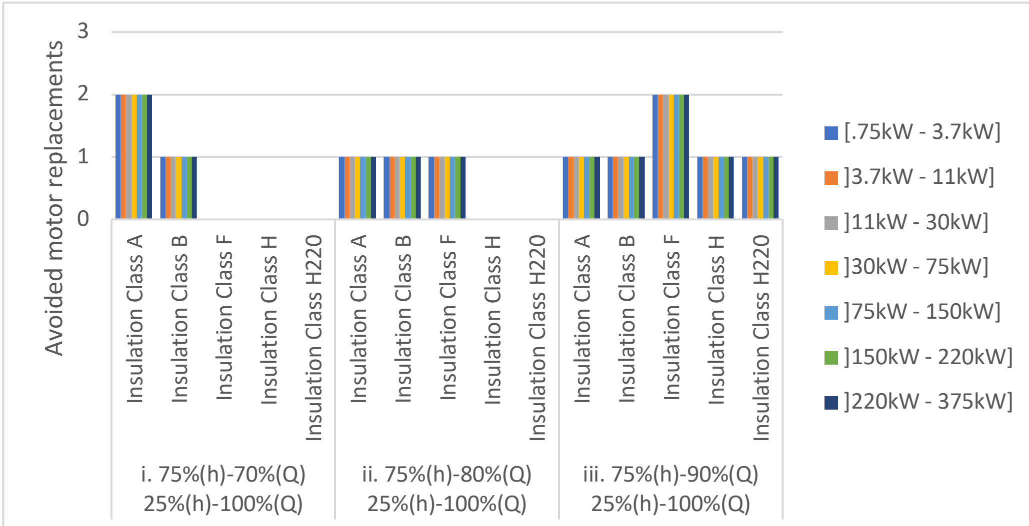

Figure 11. Average avoided motor replacements using VFD's by power range and insulation class per project lifetime

Because the installation and equipment costs are hard to estimate for every power range, the variation of the economic indicators according the different inputs tested were not considered. Nevertheless, it can be concluded that the profitability potential of the ex-ante NEB's will be inversely proportional to the EB's cost savings and of greater magnitude in countries with the combination of lowest electricity prices and highest emission factors. Moreover, it will increase in motors applications with larger power ratings, moderate reduced speeds, and motor insulation classes A or B.

10.3. Further research

Although this thesis contributes to the literature on energy efficiency by presenting a transparent method for quantifying both EB's and NEB's and by reporting the advantages of the installation of VFD's, the following suggestions for further research can be examined to broaden the horizon of the research.

- Include other control methods for the calculation of the EB's. In this thesis, the reference control method used to calculate the energy savings was throttling. Even though this the most common method to regulate flow, other types of control such as bypass and/or on-off can be included to expand the extension of the research.
- Include the study of centrifugal compressors. Like centrifugal pump and fans, centrifugal compressors are defined the Affinity laws. These devices therefore present a great potential for the research of EB's and NEB's.
- Test the calculation method in a real study case. An analysis of an actual study case can be carried out to reduce the uncertainty of the assumptions made and to test the results of the presented calculation method. In addition, an existing process can be analysed as an ex-post, so that the NEB's and their profitability potential can be studied after the implementation of a project.

Chapter 11. Conclusions

The NEB's approach appears to be a promising concept to reduce the energy efficiency gap in the industry. In this thesis, the profitability potential of NEB's brought by retrofitting electric motors with VFD's, in pump and fan applications was investigated. For this research, a method consisting of 3 phases was developed.

In the first phase, a systematic literature review was carried out to identify the NEB's in both applications. The results of this literature review were validated by conducting surveys to professionals from two of the largest drive manufacturing companies. A descriptive list including the specific NEB's, their citation number in the included literature and their contribution to competitive advantage concept resulted from this phase.

This list showed that "Improved process control", "Improved quality", "Decreased noise", "Reduced tear and wear on equipment machinery" and "Reduced emissions" and the categories "Operation and Maintenance" and "Production" are the most frequently cited NEB's in both scientific and manufacturers literature.

Moreover, it was found out that a good amount of NEB's can be brought by the use of drives in pump and fan applications. Nevertheless, it is important to consider that the benefits do not necessarily arise simultaneously, so a further assessment is needed to determine the specific benefits from an application in particular. In addition, to unlock the potential of the benefits, the technical drawbacks derived from the implementation of VFD's have to be considered and contained.

A quantification analysis was carried out in the second phase of the thesis to determine the technical and economic potential of the benefits. In this analysis, methods to quantify the EB's and NEB's as an ex-ante evaluation were investigated. The methods were selected taking into account the applicability of the benefits to every pump and fan installation, and not per a case specific. Two NEB's resulted to be quantifiable for all the applications: "Reduction of GHG emissions" and "Extended lifetime of equipment". This assessment showed that a great majority of benefits are quantifiable only as ex-post either because process specific information is required, or because some events, such as probabilities of failures, are unable to predict.

A hypothetical study case was then presented to show how the quantification of the ex-ante NEB's can impact the profitability in an investment analysis. The study case demonstrated that the profitability of NEB's in VFD applications depend on a number of variables, internal and external to the system of study, but mainly on the status of the company to be analysed and in the extension of the EB's. The EB's magnitude varies greatly according to the motor power rating and the loading schedule. EB's cost benefits are dependent upon the electricity price.

Larger power motor ratings at higher reductions of speeds presented the higher magnitude potential of EB's, and thus GHG reductions. The GHG magnitude and cost savings rely on country specific variables, namely emission factor and price of the CO_2 allowances, respectively. In the other hand, the extension in lifetime of the motor depends strongly on the reduction of load and the insulation class of the motors. Insulation classes A and B at slight reduced speeds will benefit the most. From these relations, it can be concluded that the profitability potential of the ex-ante NEB's will be greater in countries with the combination of lowest electricity prices and highest emission factors, at larger power ratings, slightly reduced speeds, and motor insulation classes A or B. Furthermore, the profitability of both ex-ante and ex-post NEB's will be inversely proportional to the EB's cost savings.

In the last phase of the research, the calculation method used to quantify the benefits in the study case was described with the help of a flow chart. The method was then compiled in a spread-sheet based model. This tool can be used as an ex-ante tool to evaluate VFD's projects. It calculates both EB's and NEB's and gives the user a certain degree of flexibility by allowing the specification of different inputs.

This model results to be a good scientific contribution as the lack transparent methods to quantify benefits of energy efficiency measures is a major barrier for effective policy making and to a more global acceptance of the energy efficiency potential in industrial motor systems.

Although a great majority of benefits cannot be quantified in an ex-ante analysis, this research provides favourable qualitative arguments for the implementation of VFD's in the industry sector, as the NEB's establish a connection to the core businesses of firms.

Lastly, this paper can contribute to overcome the barriers that have hindered the adoption of VFD's by diffusing their advantages and encouraging governments and standardization bodies to develop missing standards and regulations.

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Appendix A. Categorization of NEB's by Cooremans

BENEFITS OF ENERGY-EFFICIENCY PROJECTS (based on proven benefits of past projects)	Quantifiable (Measure - Calculation - Estimate)	Example of indicator	Contribution to operational excellence			
Be careful of double counting cascading effects !	Qualitative (Evaluation -Staff survey)	**To be related to a time period (i.e. year/month/day/hour)**	Security	Quality	Costs	Time-to -market
Waste						
Reduced waste heat	Quantitative - M	Quantity (total or as % of			x	
Used waste heat	Quantitative - M	Quantity (% of total waste heat)			x	
Reduction hazardous waste	Quantitative - M	Quantity (total or as % of	x		x	
Reduced sewage volume	Quantitative - M	Quantity (total or as % of			x	
Reduced sewage pollution level	Quantitative - M	Composition	x		x	
Reduced product waste	Quantitative - M	Quantity (total or as % of	?		x	
EMISSIONS						
Reduced dust emissions	Quantitative - M	Quantity (total or as % of	x		x	
Reduced CO, CO_2, NOx, SOx emissions	Quantitative - M	Quantity (total or as % of	x		x	
Reduction of refrigerant gases emissions	Quantitative - E	Quantity (total or as % of	x		x	
PRODUCTION						
Reduced malfunction or breakdown of machinery and	Quantitative - M	Number of breakdowns/defects	x	x	x	x
Improved equipment performance	Quantitative - E	% default pieces/pieces produced	x	x	x	x
Longer equipment life (due to reduced wear and tear)	Quantitative - E	Cost of equipment - spending			x	
Improved product quality /consistency	Quantitative - M/E	Reduction of production losses -		x	x	x
Increased production reliability (due to better control)	Quantitative - ?	% of conformity to	?	x	x	x
Larger product range	Quantitative - M	Number of additional products				
Reduced customer service costs (due to better quality)	Quantitative - E	Number of product recalls x cost of			x	
Improved flexibility of production	Quantitative - E	Time-to-market - throughput time		x	x	x
Improved temperature control	Quantitative - M	Temperature level - % default	x	x	x	?
Improved air filtration system	Quantitative - M	Air quality - % default pieces	x	x	x	?
Reduced raw material need	Quantitative - M	% raw materials - production		x	x	
Reduced water consumption	Quantitative - M	Water - production volume (or in			x	
Reduced consumables	Quantitative - M	Produits/volume prod. (ou	x		x	
Shorter production cycle (shorter process cycle time)	Quantitative - M	Duration of production time			x	x
Increased production yields	Quantitative - C	Input total/output total			x	
OPERATIONS and MAINTENANCE						
Reduced maintenance cost	Quantitative - C	Maintenance costs			x	
Reduced machinery and equipment wear and tear	?		x	x	x	
Reduced engineering control cost	Quantitative - C	Technical control cost			x	
WORKING ENVIRONMENT						
Reduced noise	Quantitative - M	Decibels x time of exposure	x	x	x	x
Air quality improvement	Quantitative - M	Number of particles /m2	x	x	x	
Improved temperature control (thermal comfort)	Quant./qualitative	Well-being	x	x	x	x
Improved lighting (visual comfort)	Quant./qualitative	Well-being - productivity		x	x	x
Improved workforce productivity	Depend on the tasks	Depend on the tasks (repetitive or			x	
Reduced absenteeism	Quantitative - C/E	Sickness absence days x cost per			x	
Reduction of health costs	Quantitative - C/E	Insurance premiums reduction			x	
Reduced need for protective equipment	Quantitative - C/E	Cost of equipment			x	
RISK REDUCTION						
Reduced risk of accident and occupational disease	qualitative - E				x	
Reduced CO_2 and energy price risks	"				x	
Reduced water price risk	"				x	
Reduced commercial risk	"				x	
Reduced legal risk	"				x	
Reduced disruption of energy supply risk	"				x	
OTHERS						
Increased installation safety	?		x	x	x	
Improved staff satisfaction and loyalty	Qualitative (S)			x	x	x
Reduced staff turnover	Quantitative - E/C	Turnover cost			x	
Delayed or reduced capital expenditure	Quantitative - C	Cost of equipment avoided			x	
Reduced insurance cost	Quantitative - E	Insurance cost			x	
Additional space	Quantitative - C	Number of m2 saved	x	x	x	
Simplification & automation of customs procedures	Qualitative - E			x	x	x
Contribution to company's vision or strategy	Qualitative - E			x		
Improved image or reputation	Qualitative (S)					

Appendix B. Categorization of NEB's by Rasmussen

Category	NEB
Waste	Reduced waste heat Used waste heat Reduction hazardous waste Reduced sewage volume Reduced sewage pollution level Reduced product waste
Emissions	Reduced dust emissions Reduced CO, CO2, NOx, SOx emissions Reduction of refrigerant gases emissions
Production	Reduced malfunction or breakdown of machinery and equipment Improved equipment performance Longer equipment life (due to reduced wear and tear) Improved product quality /consistency Increased production reliability (due to better control) Larger product range Reduced customer service costs (due to better quality) Improved flexibility of production Improved temperature control Improved air filtration system Reduced raw material need Reduced water consumption Reduced consumables Shorter production cycle (shorter process cycle time) Increased production yields
Operations and maintenance	Reduced maintenance cost Reduced machinery and equipment wear and tear Reduced engineering control cost
Working environment	Reduced noise Air quality improvement Improved temperature control (thermal comfort) Improved lighting (visual comfort) Improved workforce productivity Reduced absenteeism Reduction of health costs Reduced need for protective equipment
Risk reduction	Reduced risk of accident and occupational disease Reduced CO2 and energy price risks Reduced water price risk Reduced commercial risk Reduced legal risk Reduced disruption of energy supply risk
Others	Increased installation safety Improved staff satisfaction and loyalty Reduced staff turnover Delayed or reduced capital expenditure Reduced insurance cost Additional space Simplification & automation of customs procedures Contribution to company's vision or strategy Improved image or reputation

Appendix C. Combined list of NEB's (Cooremans and Rasmussen)

Category	NEB
Production	Shorter production cycles (shorter process cycle times) Improved capacity utilization Improved process control Increased production yields Improved product quality/consistency Improved equipment performance Improved productivity Improved production reliability Improved flexibility of production
Operations and maintenance	Reduction in labour requirements Reduction in operation and maintenance costs Reduction in raw materials and/or consumables Reduced wear and tear on equipment and machinery Reduced malfunction or breakdown of machinery and equipment Extended life of equipment Reduced need for engineering controls Improved temperature control Reduced cooling requirements Improved air filtration system Reduced ancillary operations
Waste	Reduced waste heat Reduced waste fuels Reduced product waste Reduced sewage Reduced sewage pollution level Reduced hazardous waste Reduced costs of waste disposal Reduced water consumption Reduced water losses and bills
Emissions/environment	Reduced CO, CO2, NOx, SOx emissions Reduced dust emissions Reduction of refrigerant gases emissions Reduced costs of environmental compliance
Risk reduction	Reduced water price risk Reduced legal risks Reduced carbon and energy price risks Reduced disruption risk of energy supply Reduced commercial risk
Work environment	Improved worker/installation safety Reduced risk of accident and occupational disease Reduced need for personal protective equipment Reduced health costs Improved lighting (visual comfort) Improved temperature control (thermal comfort) Improved air quality Improved aesthetics Reduced noise (auditive comfort)
Other	Improved staff satisfaction and loyalty Improved worker morale/motivation Improved workforce productivity Reduced staff turnover

Category	NEB
Other	Reduced absenteeism Improved public image Contribution to company's vision or strategy Improved competitiveness Delaying or reducing capital expenditures Reduced customer service costs (due to better product quality) Increased asset values Reduced capital costs Decreased liability Simplification & automation of customs procedures Additional space

Appendix D. Literature review (NEB's per paper)

Title	Authors	Year	NEB´s
Increasing Water Pump Station Throughput by Introducing VFD-Based IE4 Class Synchronous Reluctance Motors with Improved Pump Control	Pierre Van Rhyn Jan Harm C. Pretorius	2018	-CO2, NOx and SOx emission reductions
Life cycle cost comparison between motors equipped with variable speed drives and dampers for pumps and fans	Kanzumba Kusakana	2018	-No NEB´s reported
Considering the benefits of retrofitting centrifugal fan rotors	Devasurendra E.	2018	-Improved equipment performance
Assessing of variable speed pumps in water distribution systems considering water leakage and transient operations	Moustafa S. Darweesh	2017	-Water leak reductions in pipes -Reduce transient pressure and water loss by leakage
Maximizing Production in High Gas Wells with Electrical Submersible Pumps Utilizing Variable Speed Drives with Intelligent Gas Control Software: Case History in Colombia	J. Chira A. Diaz C. Gonzalez B. Rodriguez H. Serrano J. Prada	2017	-Increase system reliability -Increase production -Reduction of downtimes -Improved equipment performance -Faster downtime response -Reduce mechanical and electrical stresses
Medium-voltage adjustable speed drives upgrade delivers operational benefits for steel mill runout table cooling system	Durocher D.B., Magallon M.	2017	-Improved efficiency of operations -Reduced emissions
Energy saving in operations management through variable-speed drive technology: Environmental versus economic convenience	Faccio M., Gamberi M.	2017	-Better control -Low starting inrush currents -Emission reductions
Benefits of variable frequency drives on pumping systems in Enbridge liquids pipelines	André-Michel Ferrari	2016	-Less downtimes -Less failures -Increase equipment life -Increased motor reliability -Increase safety
Energy Conservation and Equipment Reliability Improvement by Operations Excellence	M. Arif N.A. Humayan	2016	-Operational flexibility -Safety (reduction in site work over operations) -Reduce downtime and improving well availability -Less stress on well at optimum operation conditions resulting in prolonged well life -Reduce maintenance cost -Increase lifetime of equipment
Variable Speed Drive (VSD) – towards modern industry and electric power systems	Sylwester Robak Jacek Wasilewski Paweł Dawidowski Marcin Szewczyk	2016	-Controlled starting current, -Reduced harmful disturbances in the power grid, -Lower power requirement of the drive at start-up, -Controlled value and characteristics of accelerations -Smooth regulation of motor speed -Controlled torque -Fully controlled drive deceleration -Power recuperation -Easy motor reverse -Elimination of additional mechanical parts

Title	Authors	Year	NEB´s
Proven methodologies for the selection of suitable applications for adjustable speed drives	Lawrence R., Heron C.	2016	-Improved process control -Improved product quality -Extended equipment life -Reduced maintenance costs -Improved visibility of the process -Fewer process interruptions
Introducing a new perspective for the economic evaluation of industrial energy efficiency technologies: An empirical analysis in Italy	Chiaroni D., Chiesa M., Chiesa V., Franzò S., Frattini F., Toletti G.	2016	-No NEB´s reported
Applying variable frequency drives to air units in industrial refrigeration systems	Douglas T. Reindl Todd Jekel John Davis	2015	-Fewer system transients -Better space temperature control -Reduced "wind chill" -Reduced noise -Inherently soft-start -Improved power factor
A practical guide for use of variable speed drives in retrofits	Paul Ehrilich	2015	-Soft start reduce wear and tear on belts, sheaves and couplings -More accurate control -Removes the need of a motor starter
Efficient energy management: is variable frequency drives the solution	Nasir Khalid	2014	-Reduced tear and wear of the motor -Reduced water hammer effect on water pipes during starting of pumps
Energy savings solutions in the Erdenet Mining Corporation	B. Sergelen	2013	-Better and smoother process control can be achieved. -Improved process flexibility -Improved process automation -Improved process control, resulting in optimizing process operation, high product quality, high productivity and high overall efficiency. -Current surges during the motor startup phase are avoided -Thermal and mechanical stresses on the machines, bearing and shafts is substantially reduced -Longer service life -Increased safety -Increased operational reliability and availability -Less maintenance
The use of variable speed drives for cost-effective energy savings in South African mine cooling systems	Du Plessis G.E., Liebenberg L., Mathews E.H.	2013	-Emissions reduction -Process control improvements -System performance and reliability improvements -Reduced maintenance by soft start and stop -Electric motor and system life extension -Power factor correction
Economic and Performance Benefits Resulting from the Use of Large Diameter Fans on Air Cooled Heat Exchangers (A Case Study in the Use of Large Fan Air Cooled Condensers at the Neal Hot Springs Geothermal Power Plant, Oregon)	Kitz, Kevin Elliott, Ryan Spanswick, Ian	2012	-No NEB´s reported

Title	Authors	Year	NEB´s
Variable Frequency Drive Applications and Their Electrical Protection Scheme for Liquids Pipelines	Oscar Ramirez Ting Yu	2012	-Flexibility in flow and pressure control -Ease of expansion without interrupting existing operations for an extended period -System redundancy -Soft start reduces mechanical stress on the pump -Less stress on mechanical and electrical equipment -Minimized throttling by controlling motor speed and providing accurate pressure control as well as proportionally maintaining energy efficiency -Power factor correction can be reduced or eliminated
A techno-economic analysis of cost savings for retrofitting industrial aerial coolers with variable frequency drives	Patrick Miller Babatunde Olateju Amit Kumar	2012	-Significantly reduces stress on the motor, bearings, and belts, which can increase the lifetime of these components -Emissions reductions
Applications of variable speed drive (VSD) in electrical motors energy savings	R. Saidur S. Mekhilef M.B. Ali A. Safari H.A. Mohammed	2012	-Flexibility and consistency of manufacturing processes -Emission reductions -Productivity improvements -Process precision -Soft start up -Improve power factor -Prolong life equipment -Reduced equipment maintenance -Improve product quality -Reduce maintenance of piping and equipment
Energy efficient technologies and energy saving potential for cold rooms	Mulobe N.J., Huan Z.	2012	-Prolong equipment life -Reduction in emissions
Energy economic and environmental analysis of industrial boilers using VSD	Atabani A.E., Saidur R., Silitonga A.S., Mahlia T.M.I.	2012	-Emissions reduction
Eco-analysis of Variable-Speed Drives for Flow Regulation in Pumping Systems	Fernando J. T. E. Ferreira João Fong Aníbal T. de Almeida	2011	-GHG emission reductions -Better process control -Less wear and tear in the mechanical components
49 exemples de bonnes pratiques énergétiques en entreprise : tertiaire, industrie, agriculture	ADEME	2011	-Case 4: The investment allowed the optimization of the safety and working conditions. Before, staff often complained of bad operation of central processing of air, now this problem is solved -Case 6: The maintenance of pumps and fans is reduced because of their less intense use -Case 8: The project has improved security and working conditions -Case 21: Improvement of qualitative for some papers produced on the site (product quality) -Case 22: Flexibility of operation Better homogeneity of the processed materials Reduced maintenance costs Reducing machine wear -Case 40: Improved quality of capsules (product quality) -Case 41: Noise reduction, reduced maintenance and extending the life of equipment. -Case 30: No NEB´s reported -Case 45: No NEB´s reported

Title	Authors	Year	NEB´s
Specialties of energy conservation and application of control systems in a large cooling water project	Relwani H., Sarma A., Salamat R.	2011	-Reduction in CO2 emissions -Less operating costs -Better process control -Less wear in the mechanical equipment -Less acoustical noise -Extended equipment lifetime
Variable frequency drives, part 2: VFD for blowers	John Dieckmann Kurtis McKenney James Brodrick	2010	-Labour reduction -Reduced noise levels -Improved comfort control
Airing out laboratory HVAC	Hock, Lindsay	2010	-No NEB´s reported
Theoretical model for evaluation of variable frequency drive for cooling water pumps in sea water based once through condenser cooling water systems	R. Harish E.E. Subhramanyan R. Madhavan S. Vidyanand	2010	-No NEB´s reported
Designing more efficient large industrial induction motors by utilizing the advantages of adjustable speed drives	Li H., Curiac R.	2009	-Reduced starting current and heat on motor -Simplification of the design in the system equipment
Watch out with variable speed pumping	Smith C.L.	2008	-Reduction in maintenance costs -Better process control
Benefits of Adjustable-Frequency Drives	Neil Koepke	2007	-Eliminate motor noise and reduce motor losses and heating -Reduced-voltage soft starter -Motor heating is reduced, allowing frequent run/stop operations
Medium Voltage Drives in the Sugar Industry	G Scheuer T Schmager	2007	-Less maintenance -Improved process control -Improved quality of the process -Lower system noise levels -Integrated motor protection equipment -Extended lifetime of motor and mechanical equipment -Elimination of motor inrush currents -Elimination of voltage sags during motor startup -Improved immunity against supply disturbances
Drives types and Specifications	Shakweh Y.	2007	-Reduced mechanical shock -Improved process performance -Improved efficiency -Reduced mechanical wear -Increased plant availability -Reduced total ownership costs -Reduced system fault levels -Reduced AC disturbances -Improved product quality -Reduction of scrap material -Improved process control -Reduce maintenance -Prolong life of equipment and the motor

Title	Authors	Year	NEB´s
Practical Aspects Regarding Implementation of Variable Speed Drives in Cooling Tower Fans	N. Muntean Sever Scridon	2006	-Avoid the mechanical stress due to the large inertia moment and to reduce the maintenance costs -Avoiding of operating at critical resonant frequencies -Eliminating of electromechanical regulation -Reducing the maintenance costs due to avoid of overloading the electrical and mechanical equipment -Rising of the technological process performances by the cooling water temperature precise control -Avoiding the ice deposits on fan wings and on the interior side of the cooling towers due to overcooling during winter
Techno-economic evaluation of energy efficiency measures in Iranian industrial 3-phase electric motors	Dalvand H., Zare M.	2006	-No NEB´s reported
Variable speed drives on fan coils yield savings	Putz C.	2006	-Increased comfort levels -Eliminates the need of manual adjustment of fan speeds -Decreased noise -Emission reductions
Technical and economical considerations in the application of variable speed drives with electric motor systems	De Almeida A.T., Ferreira F.J.T.E., Both D.	2004	-Better process control -Less wear in the mechanical equipment -Less acoustical noise -Reduced emissions
Energy efficiency of variable speed drive systems	Rooks J.A., Wallace A.K.	2003	-No NEB´s reported
Increase your profits by installing energy efficient pumps	Hamer G.	2002	-No NEB´s reported
Summary of Results for Six Industrial Market Transformation Projects Funded by the Northwest Energy Efficiency Alliance	Kenneth J. Anderson Blair Collins Amy Cortese Andy Ekman	2001	-Reduced loss of mass in apples due to better cooling control
Energy savings with variable speed drives	Pauwels K.M.	2001	-No NEB´s reported
Maintenance and production improvements with ASDs	Dolores A. R., Moran L. M.F.	2001	-Less vibration in fans, reduced noise and maintenance -Soft start prevents high currents -Extended life expectancy of the motor -Increased availability
Energy saving through VFD´s for fan drives in tobacco threshing plants	M.V. Chary N. Sreenivasulu K. Nageswara Rao D. Saibabu	2000	-Smooth speed control -Extended bearing life and pump seal life -Better process control -Trouble free operation -Improves power factor of the system -Reduces starting kva demand and cable size
Lessons learned from the U.S. DOE's motor challenge showcase demonstration projects	Szady A.J., Jallouk P.A., Olszewski M., Scheihing P.	1999	-No NEB´s reported
A Variable Frequency AC Blower Drive Installation for Efficient and Accurate Control of Glass Tempering	Stafford S. Cuffe Peter W. Hammond	1985	-Less vibration in blower and motor temperature are decreased, extending maintenance intervals -Downtime for conversion between products is reduced
Use of variable speed pumps for M S F and R O plants	Fechner G., Pillkahn R.	1985	-Increased lifetime of equipment
Motor, drives and energy conservation	Holmes Lewis	1982	-Better process control

Appendix E. Literature review (NEB's per manufacturing company)

Schneider Electric	Danfoss
Process performance improvements	Accurate process control
Predictive maintenance enhancements	Reduce maintenance costs
Improved process reliability	Enhance pump performance
Accurate flow and pressure control	Lower operating costs
Soft starting & stopping	Enables elimination of valves
Reduced lifecycle costs	Cost of changing out pumps eliminated
Extended equipment life	Lower cost of air conditioning system
Reduce emissions	Lower heat loads
Improved heat rate	Extending equipment lifetime
Higher plant availability	Optimization of processes
Improved process control	Improve pump efficiency
Lower maintenance costs	Reduce water leakage
Downtime reduction	Reduced risk of water hammer
Provide safer working conditions on site	Extended life of pipe system
Reduce labour costs	Reduce system complexity
Increase operational efficiency	Eliminating the need for an external flow sensor
Reduce total cost of ownership	improving comfort levels
Reduce your energy consumption	Comfort by avoiding frequencies that create noise and damage
Reduce waste	
Enhance safety for people, environment, and processes	

ABB	Siemens
Increased lifetime of the motor	Plant/system availability
Smooth ramp up reduces mechanical wear on the equipment	Process reliability
Increases the productivity	Breaking recovery feature
Less wear and tear on the motor and the driven machine	Integrated safety technology reduces components and wiring costs
Process accuracy	Systems can be commissioned faster
Allows the removal of valves, gears and belts	Extension of the product lifecycle of machines and systems
Reduces maintenance costs	More precise flow control with shorter response times
Maintenance without stopping the process	No pressure surges in piping systems
Enhances production output, stability and accuracy	Damaging cavitation and vibration in pumps avoided
Reduce the risk of unplanned downtime	
Reduce motor noise with spreading the switching frequencies	
Consistent product quality	
Lower fan noise level	
Avoid mechanical resonances	
Accurate speed control of the pump motor	
Accurate air flow control	
Prolong fan lifetime	
Longer life for pump and fan system	
More consistent quality and throughput of the end product	

Rockwell Automation
Help protect personnel while enabling reduced downtime
Faster time to market
Protection against unplanned downtime
Help reduce unplanned downtime

Appendix F. Surveys Results

Category	NEB	Selection times
Production	Improved productivity	6
	Improved production reliability	5
	Improved process control	4
	Improved product quality/consistency	4
	Improved equipment performance	4
	Improved flexibility of production	4
	Shorter production cycles (shorter process cycle times)	2
	Improved capacity utilization	2
	Increased production yields	2
Operations and maintenance	Extended life of equipment	4
	Reduction in operation and maintenance costs	2
	Reduced malfunction or breakdown of machinery and equipment	2
	Improved temperature control	2
	Reduction in labour requirements	1
Waste	Reduced waste heat	2
	Reduced product waste	2
	Reduced water losses and bills	1
Emissions/environment	Reduced GHG emissions	2
Work environment	Improved worker/installation safety	2
	Improved temperature control (thermal comfort)	1
Other	Elimination of additional equipment parts	1
	Improved power quality	1