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Efficiency study: Low voltage DC usage in a commercial building

A benefit analysis of two different 380V DC solutions in a commercial building

Master's thesis in Electric Power Engineering

MARTIN BEHRENDT

Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

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Abstract

The purpose with this thesis is to answer what value a commercial building 380V DC solution holds, in regards to energy and financial savings, in comparison to an equivalent AC system. Energy savings are investigated in the distribution system and in the load conversion steps. This work is purely an efficiency study, no regards has been taken to system reliability or safety aspects. Two different 380V DC solutions has been evaluated, one referred to as the *DC solution* and the other one as the *optimized DC solution*, where the latter use loads which are optimized for DC usage, with no unnecessary power electronics. Efficiencies are studied for distribution system, photovoltaic system and chosen loads such as data center, lighting, ventilation fans and receptacles (process energy). Load profiles are created and scaled with efficiencies corresponding to each system, AC, DC and optimized DC. The AC system is used as a reference system and the difference in required energy between the systems are simulated on an hourly basis. This is done for thee difference load points, 20%, 50% and 80% of maximum load and for weekdays, Saturdays and Sundays, resulting in nine different cases per system evaluated. This resulted in, for the DC solution, energy savings ranging between -29 450 kWh/year (-0.8%) to 109 119 kWh/year (3.2%), resulting in yearly financial savings of €-1 458 to €5 401. For the optimized DC solution, energy savings ranges between 164 234 kWh/year (4.4%) to 276 352 kWh/year (8.2%), resulting in yearly financial savings of €8 130 to €13 680. The DC solution were found non-feasible, the shortest payback-time were found to be 34 years, thus longer than the expected equipment life-time. The optimized DC solution payback-time were found to range between 14 and 23 years, with an even load distribution between the three load points the payback-time was found to be 17 years. Thus, even in worst case, the optimized DC solution is still feasible, with an overall system efficiency gain of 4.4% and yearly financial savings of €8 130.

Keywords: Building Efficiency, DC Grid, Low Voltage DC, Load Profiles, Rectification, Inversion, FEBDOK Simulation, Practical Efficiency Measurements, Photovoltaics.

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Martin Behrendt, Gothenburg, February 2017

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1
Introduction

In Europe, buildings are responsible for approximate 40% of the total energy consumption and 36% of the total CO_2 emissions [1]. With this knowledge, it is safe to say that energy efficient buildings is something to strive for, both for environmental and financial reasons. This thesis is written in collaboration with WSP, which is one of the worlds leading engineering consultant firms. WSP have approximately 36 500 employees, spread amongst 40 countries and 500 offices [2]. WSP is partly responsible for a large building project in Gothenburg, Sweden, the project and the name of the building will be referred to as *Platinan*. Platinan is a 60 000m^2 building, containing several different service areas such as office space, hotel, restaurants, retail and garage [3]. In Platinan, new methods of financial savings are investigated. One such method, is an old technology but with relatively new areas of application, namely the usage of direct current (DC) in buildings. The background to the interest in DC is due to the assumptions that there will be lower distribution losses and less conversions steps, contributing to a higher overall system efficiency. One could also argue that with photovoltaic energy production vastly increasing and with today existing energy storage techniques, that DC is of superior compatibility over alternating current (AC) [4][5].

1.1 Purpose

The purpose with the thesis is to answer what value a commercial building 380V DC solution holds, in regards to energy and financial savings, in comparison to an equivalent AC system. Potential energy savings will be investigated in the distribution system and in the load conversion steps.

1.2 Method

Load information is gathered and load profiles are merged in *Matlab*, creating ideal case (loss less) load profiles. The ideal load profiles are then scaled with efficiencies for the different loads corresponding to the standard AC case and to the two suggested DC solutions. Efficiencies are found through practical measurements, in theory and through simulations. The difference in energy between the scaled load profiles are summarized and weighted based on different load distributions. The lowest and highest profit are looked upon to find the minimum and maximum savings in both energy and money. More information regarding the different cases investigated and evaluated are presented in chapter 3, *Case Setup*.

2

Theoretical Background

2.1 Distribution System

The earthing network should be of type TN, regardless of AC or DC distribution low voltage system, in Sweden [11]. Figure 2.1 illustrates a five conductor distribution system for AC, consisting of three phase conductors (L_1-L_3), neutral conductor (N) and protective earth conductor (PE) [6]. Figure 2.1 also illustrates a large consumer connected to three phases and a smaller consumer connected to a single phase.

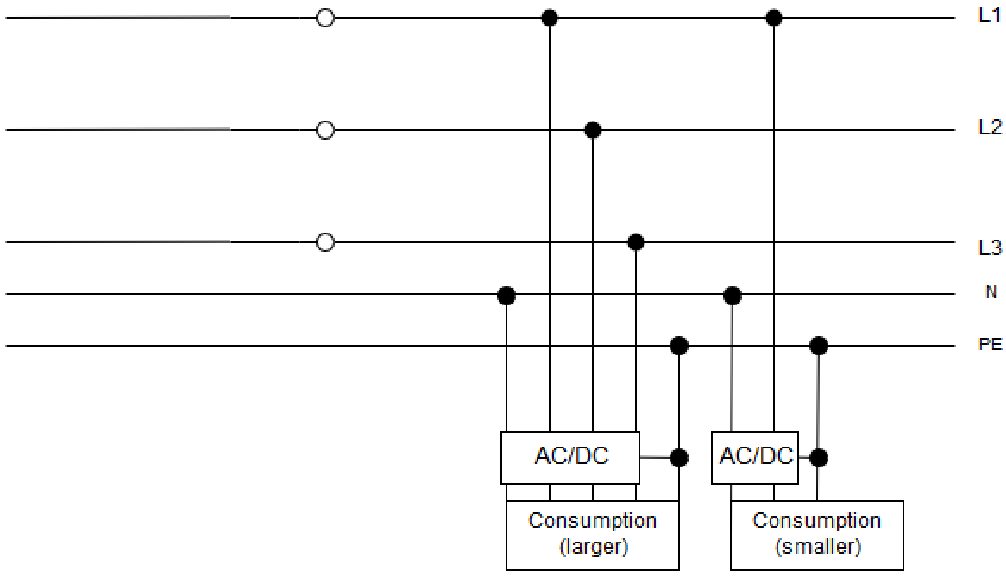


Figure 2.1: Five conductor TN network for AC distribution [6].

Figure 2.2 illustrates a four conductor distribution system for DC, consisting of one positive and one negative phase conductor (L+ and L-), neutral conductor (M) and protective earth conductor (PE). In accordance with figure 2.1, figure 2.2 also illustrates one larger and one smaller consumer and the corresponding connections.

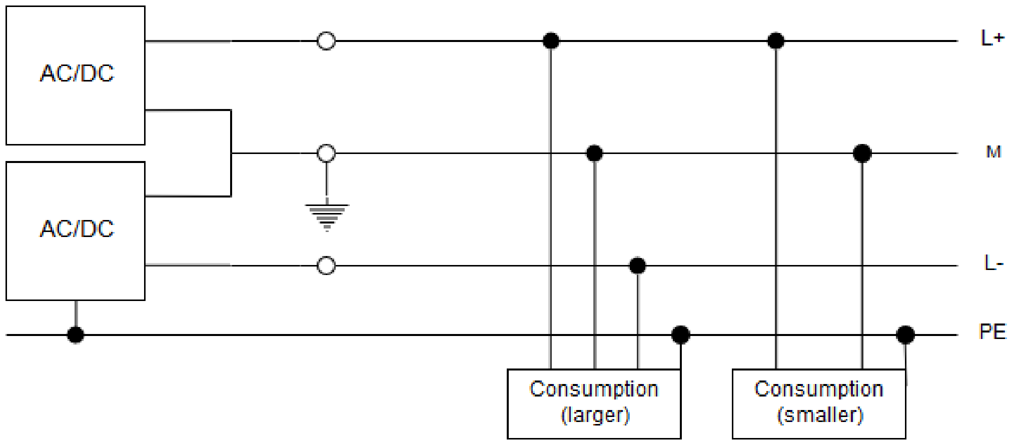
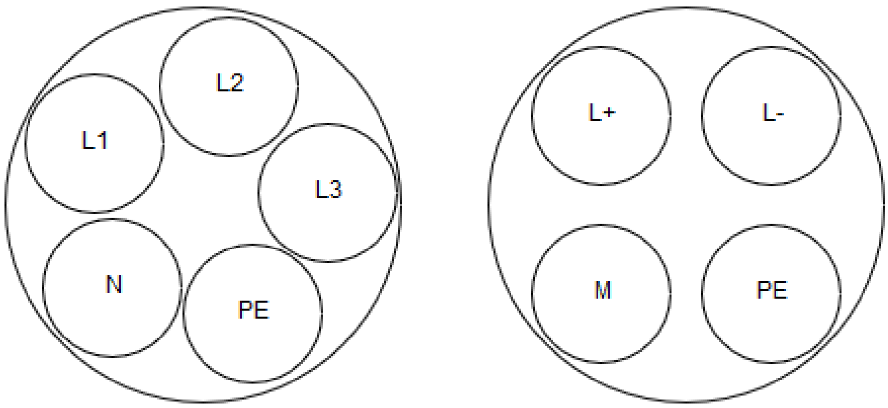


Figure 2.2: Four conductor TN network for DC distribution [6].

Figure 2.3 illustrates a cross-section of a AC five conductor cable and a DC four conductor cable respectively.



(a) AC cable with five conductors

(b) DC cable with four conductors

Figure 2.3: AC and DC cable illustration, with five and four conductors respectively.

2.1.1 DC Distribution Losses

A circuit representation of a DC distribution cable can be seen in figure 2.4. The cable is represented as consisting of a resistive part. The resistance of a copper conductor at a temperature of 20°C is equal to

$$R = \rho \frac{l}{A} \quad [\Omega/m] \tag{2.1}$$

where ρ, l and A represent conductor resistivity, length and cross-section area, respectively [10]. The conductor resistance is dependent on conductor temperature, the relation is as follows

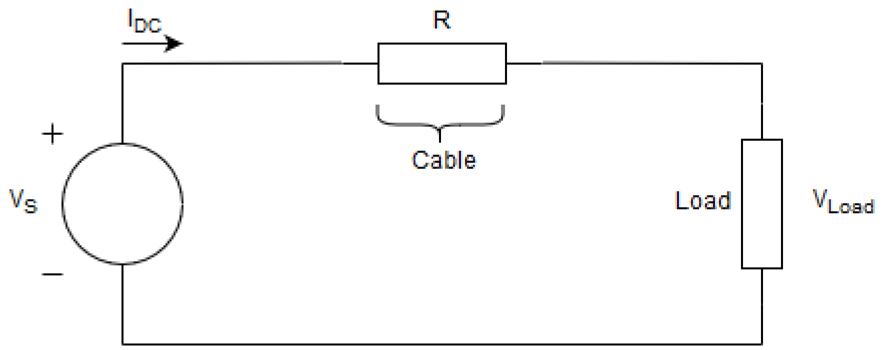


Figure 2.4: Circuit representation of a DC cable consisting of a resistive part.

$$R_{temp,dep} = R \cdot [1 + \alpha(t - 20°C)] \quad [\Omega/m] \tag{2.2}$$

where α is the resistance temperature coefficient and t is the conductor operating temperature in degrees celsius [8]. The voltage drop over the cable in figure 2.4 is given by

$$V_{DC,drop} = RI_{DC} \quad [V] \tag{2.3}$$

and the power loss over the cable is given as

$$P_{DC,loss} = RI_{DC}^2 = V_{DC,drop}I_{DC} \quad [W]. \tag{2.4}$$

2.1.2 AC Distribution Losses

A circuit representation of an AC distribution grid can be seen in figure 2.5. The cable is represented as consisting of both resistive and an inductive part.

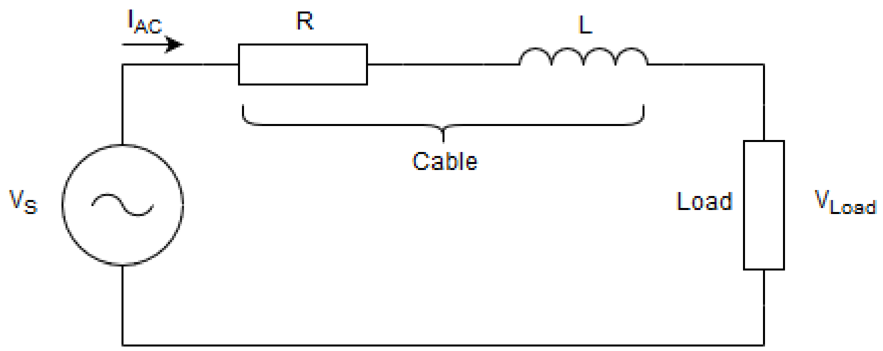


Figure 2.5: Circuit representation of an AC grid, where the cable consisting of resistive and inductive part.

The resistance, R, is calculated as seen in (2.2), it is assumed that the resistive part is equal in the DC and AC case. To calculate the inductive part of the circuit, the inductance for two parallel wires formula is used

$$L = [0.05 + 0.2 \cdot ln(\frac{a}{r})] \cdot 10^{-6} \quad [H/m] \tag{2.5}$$

where a is the distance between the conductors and r is the radius of the conductors [9]. For a, an average value between the minimum and maximum value is used. The impedance, Z, of the circuit in figure 2.5, is given by

$$Z = \sqrt{R^2 + X^2} = \sqrt{R^2 + (2\pi f L)^2} \quad [\Omega] \tag{2.6}$$

where X is the reactance of the circuit and f is the frequency which is assumed to be constant at 50Hz. The voltage drop over the cable is given as

$$V_{AC,drop} = Z|I_{AC}| \quad [V] \tag{2.7}$$

and the power loss over the cable is given as

$$P_{AC,loss} = Z|I_{AC}^2| = V_{AC,drop}|I_{AC}| \quad [W]. \tag{2.8}$$

2.1.3 Single Line Current

For a single line conductor the difference in current for the DC and AC case is dependent on the used voltage level. As an illustrating example, for a specific load with power demand P_{demand}, both P_{DC} and P_{AC} need to be equal to P_{demand}.

$$P_{DC} = P_{AC} \rightarrow V_{DC}I_{DC} = V_{AC}|I_{AC}| \rightarrow I_{AC} = (\frac{V_{DC}}{V_{AC}}) \cdot I_{DC} \quad [A] \tag{2.9}$$

Thus, the difference in current between DC and AC is the ratio of the relation between the DC and AC voltage level.

2.2 Power Electronics

In this section, important processes for this report are described. Different loads demand different type of voltage, some demands alternating and some constant voltage, as a solution to this, voltage conversion devices are used. Power electronics such as rectifiers and inverters enables flexibility, but comes with a cost, namely losses.

2.2.1 Rectification Process

The rectification process is when there is an alternating voltage as input and a constant voltage level as output. For a single phase voltage, this can be achieved using a single phase diode bridge rectifier. As illustrated in figure 2.6, where V_s is AC voltage and V_s is DC voltage, the rectifier is idealized such as that there is no source inductance. This is a simple example of rectification, in reality, this bridge rectifier is only one step in a longer process. The entire process can be seen in figure 2.7, where the additional steps are filtering and voltage level regulation.

The function of the single phase rectifier in figure 2.6 is described below:
Positive half-cycle: The source voltage, V_s and the source current, i_s, goes through diode D1 and returns through diode D2.
Negative half-cycle: The source voltage, V_s and the source current, i_s, goes through diode D3 and returns through diode D4. In this part of the cycle, the source current goes in the opposite direction compared to i_s in figure 2.6 [12].

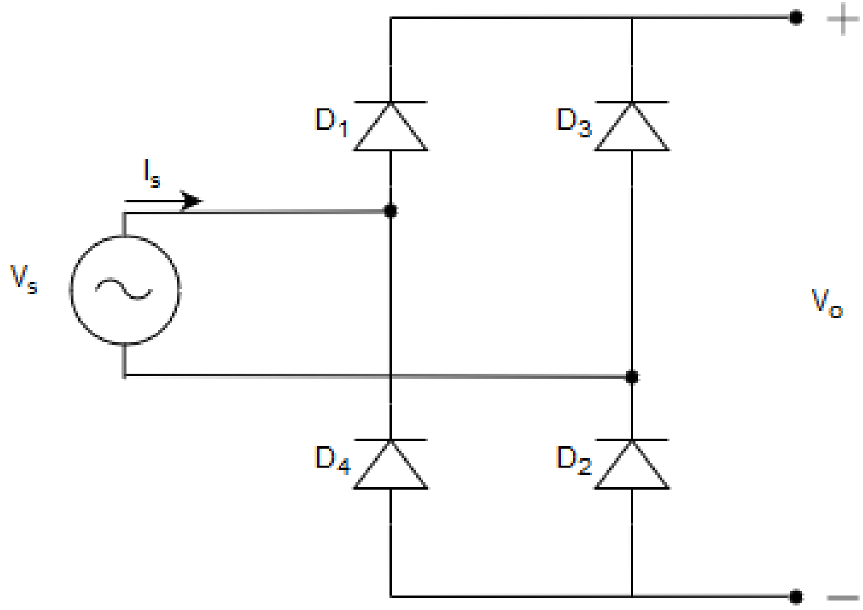


Figure 2.6: Single phase diode bridge rectifier [12].

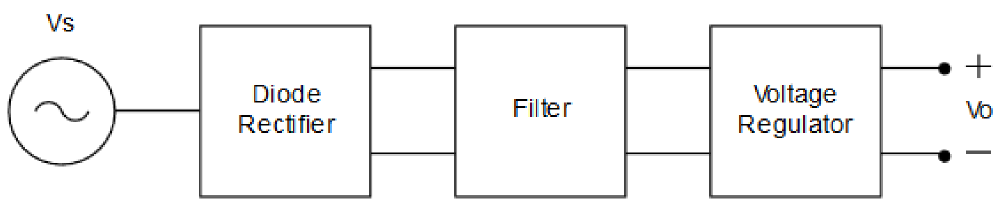


Figure 2.7: Block diagram of a simple rectification process [7].

2.2.2 Inversion Process

As an opposite to rectification, there is inversion, converting DC input voltage to AC as output voltage. A single phase full-bridge inverter is shown in figure 2.8. In this example, the source voltage, V_s, is a constant level DC voltage. There are several ways to operate the inverter to get the desired alternating output voltage. Used operating modes are for example pulse width modulation or square-wave mode, where the former can be either bipolar or unipolar switching [12]. There will be no further explanation of the operation control modes, just the assumption that any inverter will be able to deliver an useful alternating voltage and current. In resemblance with the rectification process, the inversion process can also contain filtering.

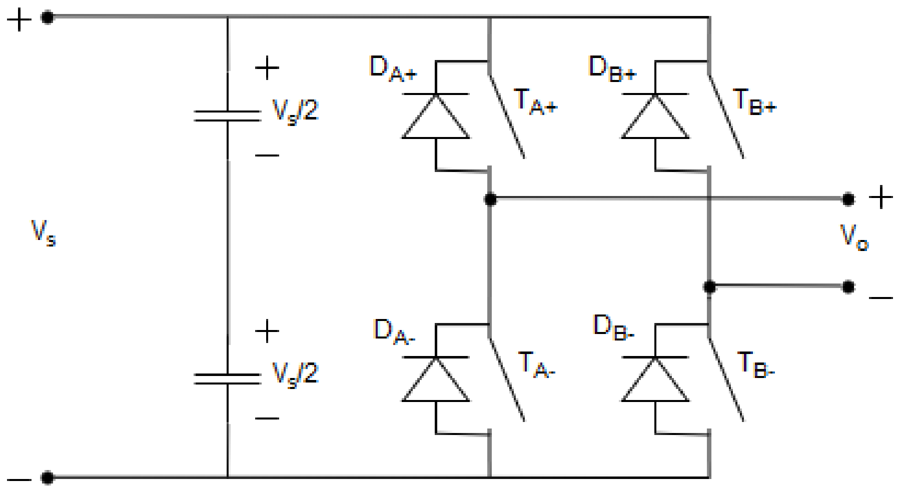


Figure 2.8: Single phase full-bridge inverter [12].

2.3 DC loads

In this report the following loads are studied; data center, lighting, ventilation fans and receptacle loads. The decision of which loads to study is based on product availability and on aspects that are of interest for WSP. These loads are of no means the only ones possible to use with DC, but due to project time limitation the above mentioned product limitation is made.

2.3.1 Data Center

This section contains a description of the components in a typical data center as well as typical layouts for AC and DC data centers respectively. First in line is the uninterpretable power supply (UPS), which enables power supply to the server loads both at normal operation and at a potential power outage, to protect critical loads. There are many different UPS topologies, but the double conversion on-line UPS is the most common for sizes above 10kVA [23]. The double conversion on-line UPS can be operated in Normal-mode or in Bypass-mode, where the latter is also referred to as Eco-mode. Figure 2.9 illustrates the double conversion on-line UPS, where in Normal-mode the power go through the two conversion stages, which result in lower efficiency but higher reliability. In Eco-mode, the power goes through the static bypass switch, which enables higher efficiency, but exposes the sensitive load to raw voltage mains supply. It also increases the time to switch to battery drive if a power disturbance occurs [22]. Figure 2.9 also illustrates a maintenance switch which is only active during maintenance, this switch is not a part of the actual topology, it is an external feature.

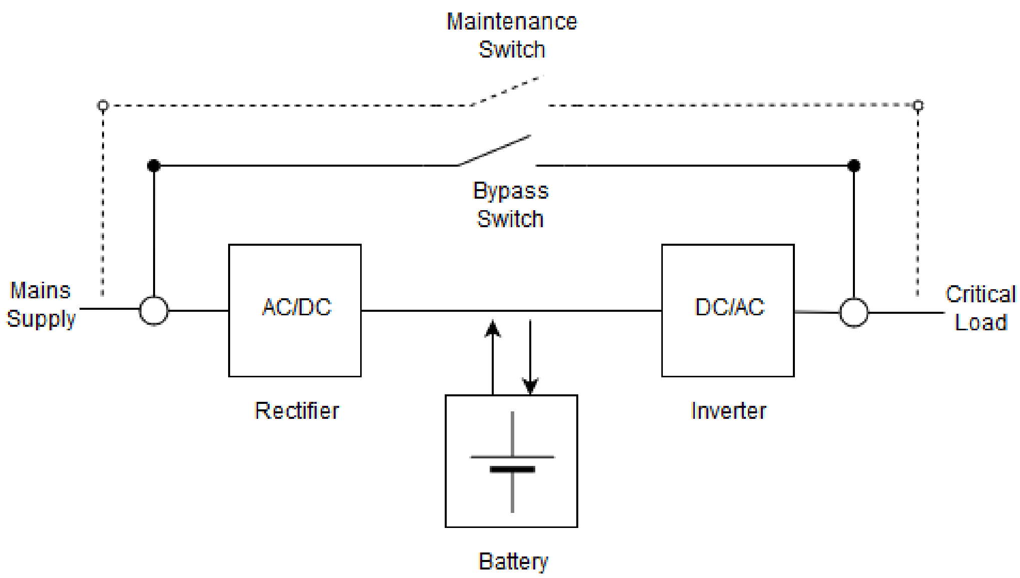


Figure 2.9: Double conversion on-line UPS topology [22][40].

Because of the fact that when it comes to the UPS, reliability and load protection is the main priority. Thus, this work will assume Normal-mode operation for comparison [40]. In figure 2.10 and 2.11, typical data center layouts for AC and DC are shown. It is quite clear that the typical DC layout contains fewer conversion steps. The power path in this report is set to start with the UPS described above and end with the server load. The power distribution unit (PDU) or power strip, distributes the power to the different servers and often offers control and monitoring capabilities. The power supply unit (PSU), supplies the internal loads such as servers and fans with low voltage [19][20].

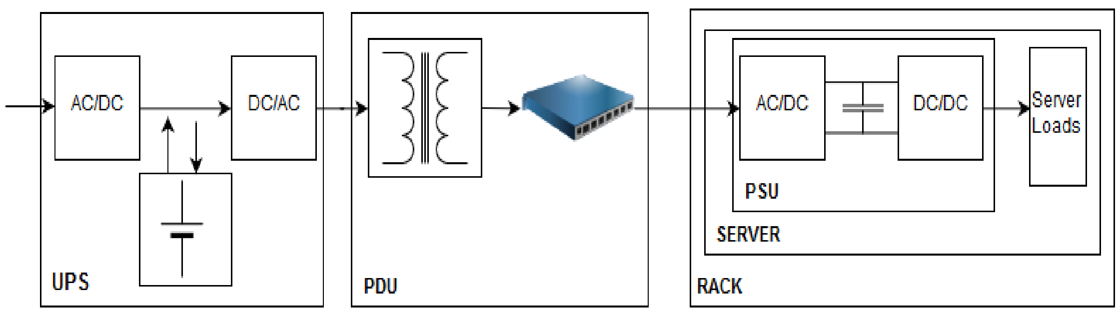


Figure 2.10: Typical AC data center layout [19].

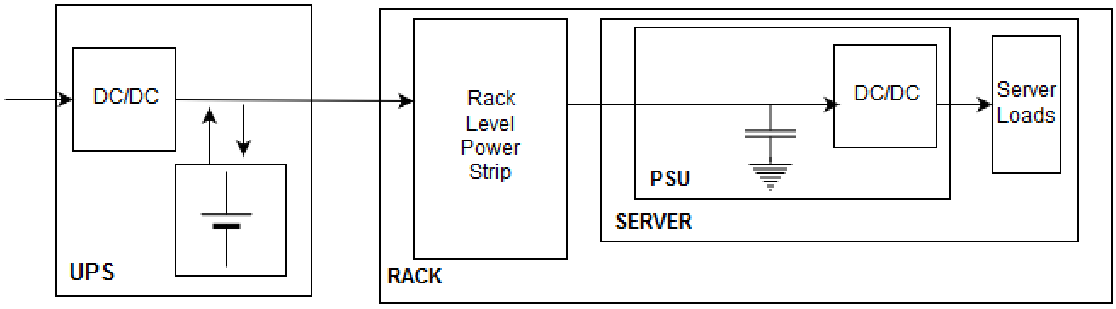


Figure 2.11: Typical DC data center layout [19].

2.3.2 Lighting

Losses regarding lighting in this report will be investigated at the ballast. There are several different types of ballasts, in figure 2.12, the principle of a high-frequency ballast is illustrated. This type of ballast supplies e.g. fluorescent tubes, which requires AC.

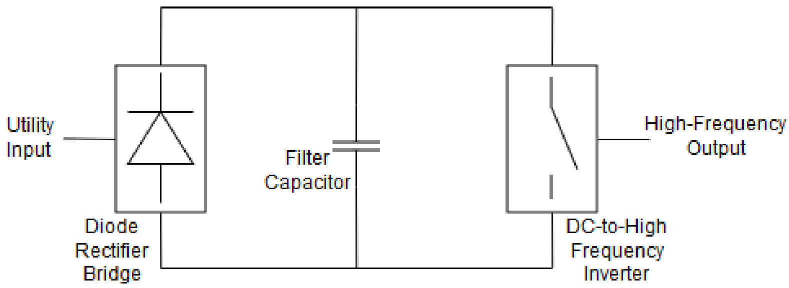


Figure 2.12: Block diagram of a high-frequency fluorescent lighting ballast [12].

For other lighting sources, such as a light emitting diode (LED), a ballast such as illustrated in figure 2.13 can be used. In this ballast, the desired output, V_o, is DC voltage. Thus, there is no need to invert the voltage, in comparison with the previous ballast in figure 2.12. It might be necessary to regulate the output voltage to an appropriate level for the LEDs.

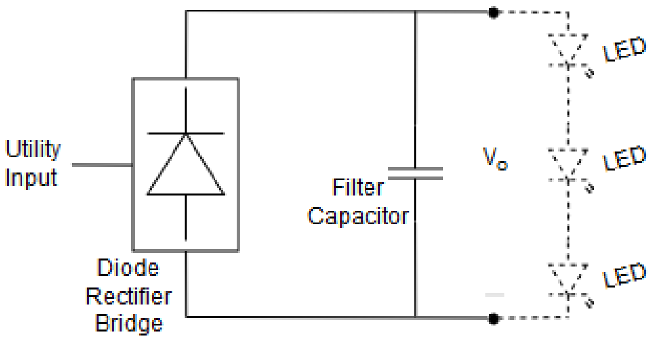


Figure 2.13: Block diagram of a LED ballast, where no inversion process is necessary.

2.3.3 Ventilation Fans

When dimensioning the ventilation system in a building, the fan power can be determined using the Specific Fan Power (SFP) formula

$$SFP = \frac{P_{el,to} + P_{el,from}}{Q_{max}} = \frac{P_{el,max}}{Q_{max}} \tag{2.10}$$

where Q_{max} is the dimensioning air flow in the building, $P_{el,to}$ and $P_{el,from}$ is the electrical fan power needed to drive the air "to" and "from" the ventilation system [13]. Summarizing these two power-terms resulting in the maximum dimensioning electrical fan power, $P_{el,max}$. With some arrangements of (2.10), $P_{el,max}$ can be written as

$$P_{el,max} = SFP \cdot Q_{max} \quad [W]. \tag{2.11}$$

2.3.4 Receptacles

Receptacle loads are often referred to as process loads or process energy, if talking about consumption. In this report these loads will be referred to as receptacle loads only. In table 2.1, a small selection of receptacle loads with power, voltage and current are listed, it can also been seen which loads that are compatible with DC usage. There are many other types of receptacle loads, table 2.1 function is to provide an understanding of what potential receptacles are.

Table 2.1: Power rating, voltage and current for a small selection of receptacles present in the building [14][15][16].

Load	Power [W]	Voltage [V]	Current [A]	DC Compatible
TV, 50"-55" LED	100	380	0.26	Yes
Laptop	60	380	0.16	Yes
Desktop	100	380	0.26	Yes
Mobile phone	3	380	0.008	Yes
Monitor, 27"	35	380	0.10	Yes
Coffee maker	1 000	380	2.63	Yes
Water kettle	2 000	380	5.26	Yes
Refrigerator	100	380	0.26	Yes
Dishwasher	1 300	380	3.42	Yes
Washing machine	500	380	1.32	Yes
Induction Stove	7 200	380	18.95	Yes
Tumble dryer	4 000	380	10.53	Yes
Microwave oven	1 000	380	2.63	No
Electric oven	2150	380	5.66	No
Electric stove	2000	380	5.26	No

All ratings in table 2.1 are approximate and are likely to vary between different products and manufactures. In this work, 10% of all receptacle loads will be assumed to require 50Hz AC as supply voltage to function, these loads are referred to as *AC receptacles*.

3
Case Setup

3.1 Case Definition

To be able to quantify the DC solutions profit, one must compare with an equivalent AC system. To make the comparison just, load profiles will be determined for the different loads, one for a weekday, Saturday and Sunday respectively. This section contains important information and reasoning regarding the cases and structure of the report.

3.1.1 AC, DC and optimized DC

An ordinary AC system is per default used as reference, all comparisons is towards an AC system. AC loads are not always, but often equipped with some kind of power electronic component, with the target to rectify the alternating voltage and current, as mentioned in section 2.2. In this report, the *DC solution* refers to a solution where DC is used as utility voltage, but the loads are the same as for the AC case, thus not optimized for DC usage. This means that losses still occurs in the loads' rectifier. An example of this DC solution usage is at the Swedish Department of Energy Headquarters in Eskilstuna, a specially made socket outlet was made, it can be seen in figure 3.1. The second DC solution is name *optimized DC*, shorted DC_{opt}. In this solution, loads previously consisting of rectifier power electronics are now removed. Thus, the loads are optimized for DC operation. Throughout the report, the DC and DC_{opt} solutions are compared to the standard AC solution. If nothing is specified for DC_{opt}, it is assumed that it works similar to the DC solution.

3.1.2 Weekdays, Saturday and Sunday

Platinan consist of different operations, there are office activity, hotel, retail, garage and common spaces usage. Different activities are active at different points of time, for example, to take office operation for one weekday and multiply that consumption by seven to get a whole week is clearly misleading. For this reason, this report consider weekdays and weekends, in form of both Saturdays and Sundays when creating the load profiles.

3.1.3 Load Points

It is well known that the working interval for rectifiers and inverters, the efficiency is seldom constant, it varies with load output. Due to the verity of demand in

Figure 3.1: Specially made socket outlet for DC, picture is taken at the Swedish Department of Energy Headquarters in Eskilstuna.

Platinan, three working point will be used throughout the report. Firstly, the lowest working point, referred to as low load case, which is equal to 20% of maximum load. Secondly, the medium working point, referred to as the normal or medium working point, which is equal to 50% of maximum load. Thirdly, the highest working point, referred to as high working point, which is equal to 80% of maximum load. Each load will be scaled with corresponding efficiencies for the three different load points, providing more depth between the comparison of the systems.

3.2 Alternating and Direct Voltage Levels

The distribution electricity mains in Europe is 230V AC, with an additional tolerance of ±10%. Leading to the highest acceptable AC rms voltage in the utility grid equal to 253V AC [17]. This result in the highest acceptable AC peak voltage of

$$V_{AC,peak} = \sqrt{2} \cdot 1.1 \cdot 230V = \sqrt{2} \cdot 253V \approx 358 \quad [V]. \tag{3.1}$$

There is a discussion if the optimal DC voltage level to use is 350V DC or 380V DC, both have pros and cons. The alternating voltage peaks at ±358V, as illustrated in figure 3.2, together with the the two DC voltage levels in question and with the alternating voltages' corresponding rms-value. As seen in figure 3.2, the lower level constant DC voltage can be used as supply voltage for AC/DC loads, due to the fact that its level does not exceed the maximum alternating voltage value. The higher

DC level voltage on the other hand, do exceed the alternating voltage maximum value. This means that existing everyday AC adapters could be DC fed without changing any of the existing hardware, if using 350V DC. Thus, one argument for a lower DC level, is to be able to DC feed a larger segment of existing receptacles without changing the hardware. The higher ±380V DC level though, enables lower current and as mentioned previously, this is the voltage level that will be used in this work.

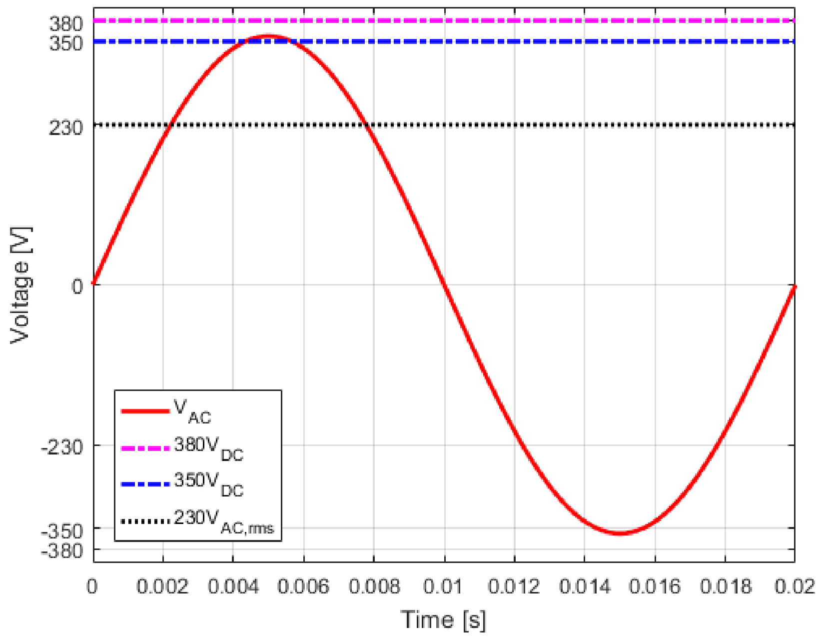


Figure 3.2: The AC, two DC and AC$_{rms}$ voltage level comparison.

3.3 Load Profiles

The load profiles are made from material provided from WSP and a building performance rating method, called ASHRAE [41]. Due to the early state of the project, information may not be available, if so, assumption have been made and stated. For simplicity reasons, each load will be considered individually, before merging all loads. The following sections will determine the load profile for the medium demand case, which as mentioned corresponds to 50% of maximum load.

3.3.1 Data Center

The data center consists of 16 server racks, an approximate power capacity per rack has been assumed to be 6kW [18]. Thereby the total maximum data center power is 96kW, as seen in table 3.1.

Table 3.1: Number of racks, power density per rack and total data center power.

No. of Server Racks	Rack Power [kW]	Total Power [kW]
16	6	96

The medium load condition which is assumed to be 50% of maximum load, thus resulting in the following load profile, see figure 3.3.

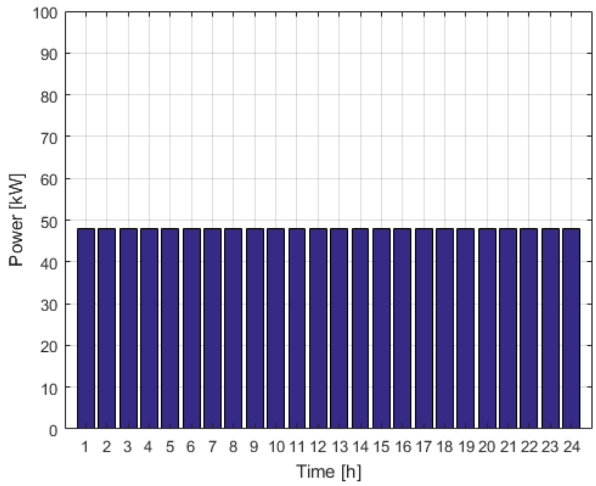


Figure 3.3: Data center load profile, 50% load for Weekdays, Saturday and Sunday.

It is difficult to get a fair picture of the overall data center system performance, due to many different products and manufacturers. In table 3.2, conflicting efficiency improvements when switching from AC to DC driven data centers are showed.

Table 3.2: Reported DC data center efficiency improvements from different reports.

Report	Efficiency Improvement [%]	Reference
ABB	10	[20]
Delta	7	[19]
LBNL	4.7-7.3	[24]
Schneider	0-1	[21]

As seen in table 3.2, the reported efficiency improvements vary significantly. These variations is due to three substantial factors:

1. The start and end point of the system power path; Commonly throughout the reports the power path starts at UPS and ends at server load. This is especially true for small and medium scale data center integrated in commercial buildings. The power path in ABB's report is longer, from a HVAC grid to the server loads, enabling more opportunities for efficiency improvements, their report is done for a large scale stand-alone data center.

2. AC reference system; Reports comparing the newest DC technology to older existing AC system of course result in misleading high efficiency improvements.
3. Constant or variable load; The efficiency for all inverters or rectifiers are seldom constant, as mentioned, it varies based on output power. The most just comparison between system is thereby made by looking at several working points of the system, going through the devices efficiency interval. If there is no possibility to measure and plot the different efficiency curves for the devices along the power path or if they are not published by the manufacturer, a single working point has to be sufficient. This then needs to be considered when comparing systems.

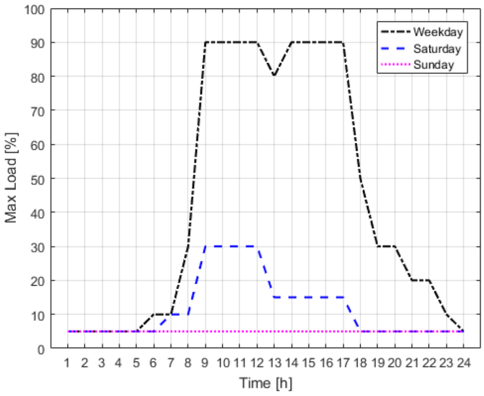
3.3.2 Lighting

The building will consist of many different lighting sources, approximately 60 different types, with varying rated power. They are made from different manufacturers and uses different ballasts. Due to the complexity of making a load profile based on all these different lighting sources and their respective ballast, an assumption is made. The assumption is that all lighting sources within the building are LEDs with rated power of 25W and uses the LED-drive (ballast) mentioned in section 4.2.2, with rated power of 30W. In table 3.3, the distribution of the lighting sources within the building is shown, categorized by area. It also shows the total power in kW, for each area and for the entire building. The restaurant lighting is included in the *Hotel* category and public areas such as staircases, technical areas and toilets are included in *Other* category.

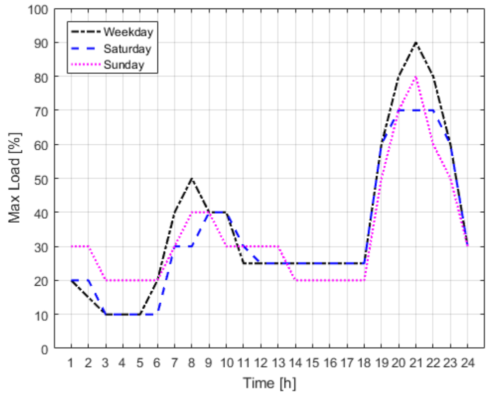
Table 3.3: Distribution of lighting sources within the building, categorized by area with corresponding power per area.

Area	No. of lighting sources	Lighting-source Power [W]	Total Power [kW]
Office	7 092	25	177.3
Hotel	9 181	25	229.5
Retail	150	25	3.8
Garage	179	25	4.5
Other	2 177	25	54.4
Total	18 779		469.5

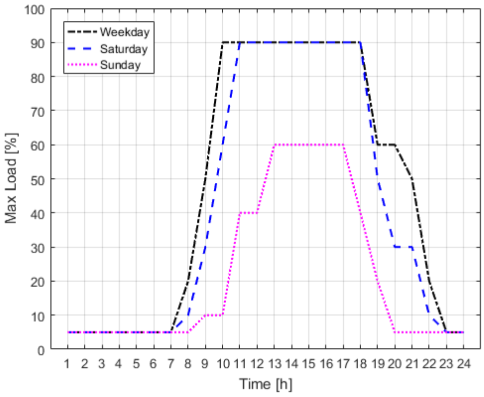
Below in figure 3.4, the lighting load profile categorized by area is shown, as percentage of maximum load over time. Each figure 3.4a-3.4e, consist of three curves; weekday loading, Saturday loading and Sunday loading. The loadings from figure 3.4 together with the lighting power from table 3.3 provides the total lighting power demand in the building for a weekday, Saturday and Sunday respectively. This can be seen in figure 3.5.



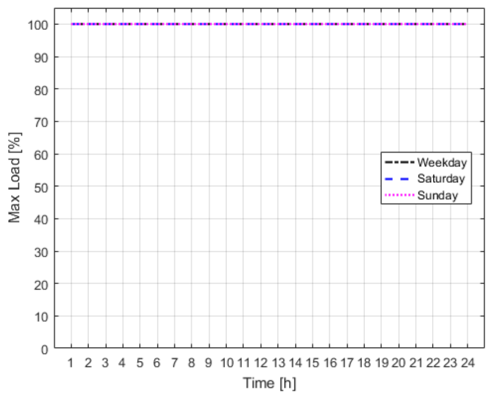
(a) Office lighting



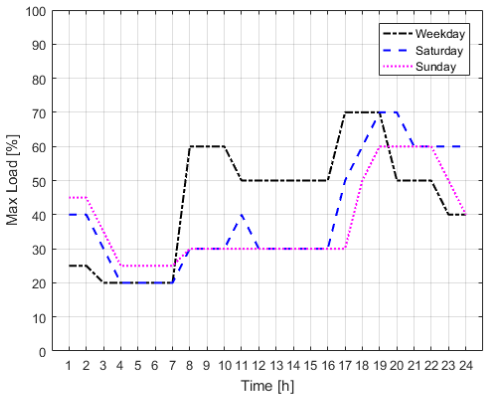
(b) Hotel lighting



(c) Retail lighting

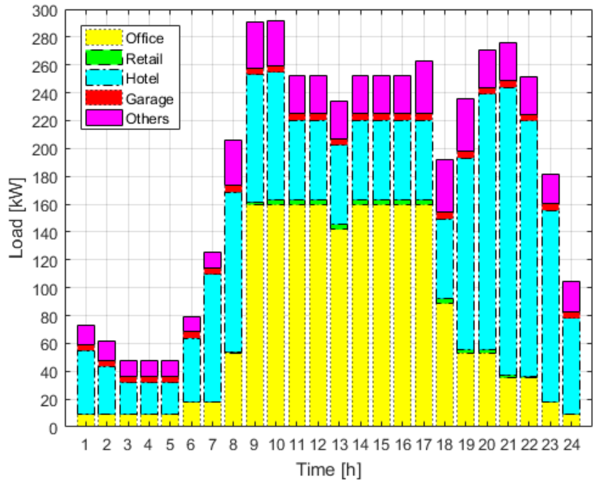


(d) Garage lighting

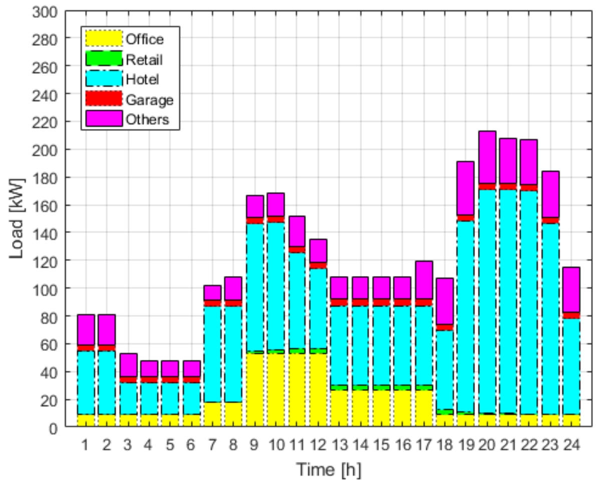


(e) Other lighting

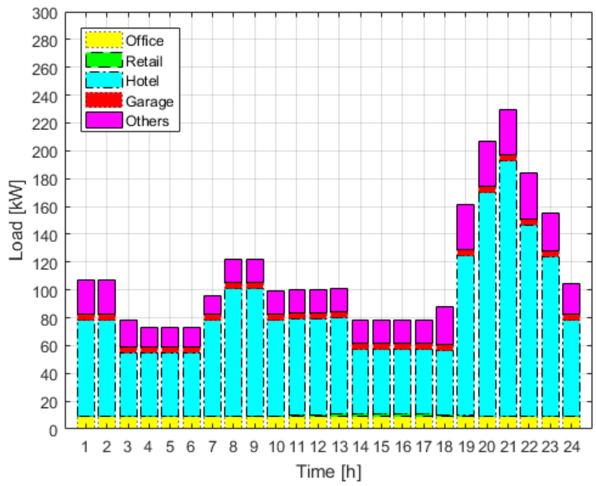
Figure 3.4: Loading in percent of maximum load for weekdays, Saturday and Sunday for the different areas [41].



(a) Weekday lighting consumption



(b) Saturday lighting consumption

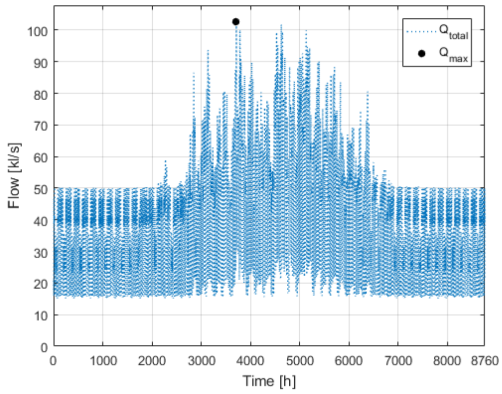


(c) Sunday lighting consumption

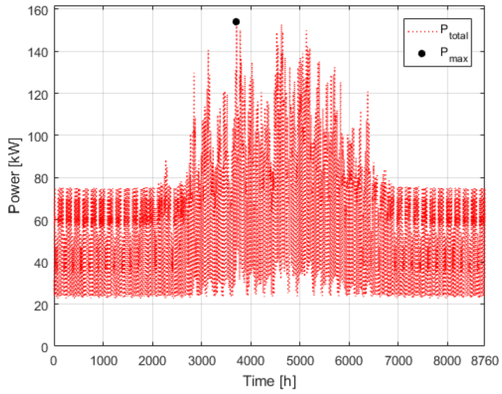
Figure 3.5: Lighting load profiles for weekdays, Saturday and Sunday.

3.3.3 Ventilation Fans

Below in figure 3.6, the total air flow and corresponding power is shown. The air flow is simulated over one year and (2.11) from section 2.3.3 is used, with SFP=1.5, to acquire the fan power. The simulation is carried out in *IDA*, by a third part. The maximum fan power, P_{max}, equals to 154kW.



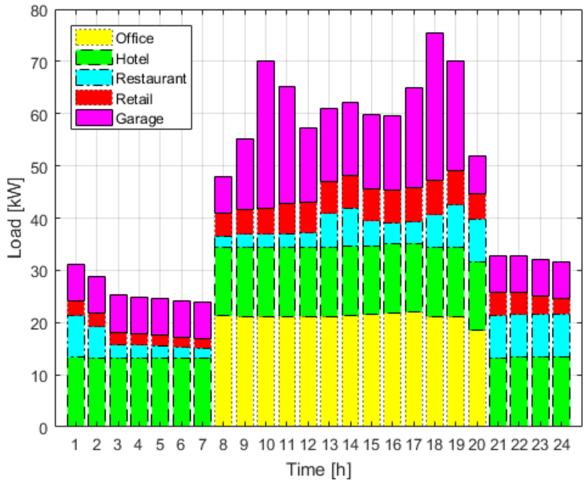
(a) Total fan air flow



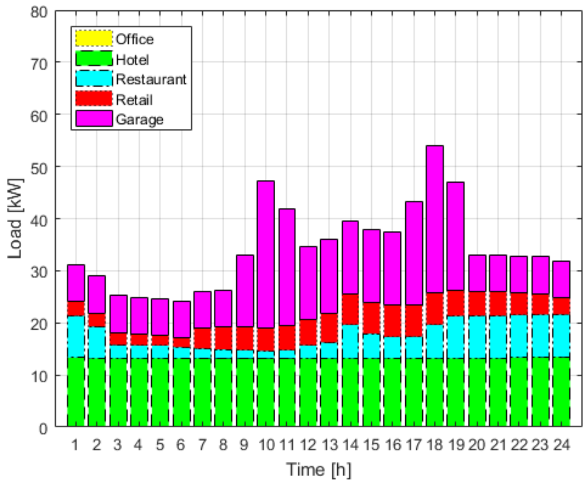
(b) Total electrical fan power

Figure 3.6: Illustrates simulation results of the building air flow and electric fan power. Figure 3.6a illustrate the maximum air flow point which is the dimensioning factor for the maximum electrical fan power seen in figure 3.6b.

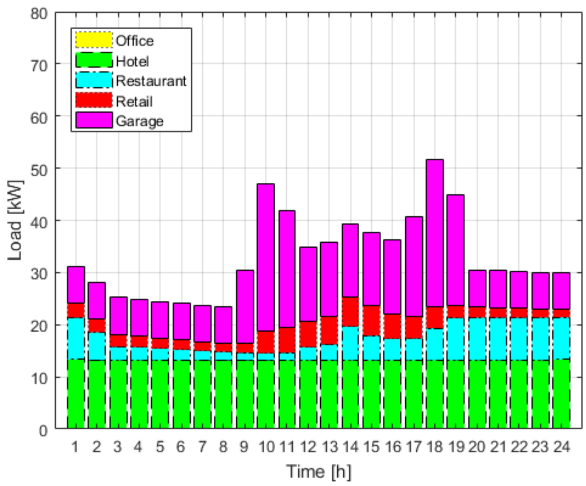
As seen in figure 3.6b, the required fan power is relatively constant between the hour interval of 0-2800 and 6200-8760. Since this interval represents a majority of the year, the load profile for the ventilation fans will be based on this lower power level. In figure 3.7, the first hours of the interval have been used to illustrate the fan power consumption for one weekday, Saturday and Sunday.



(a) Weekday fan power consumption



(b) Saturday fan power consumption

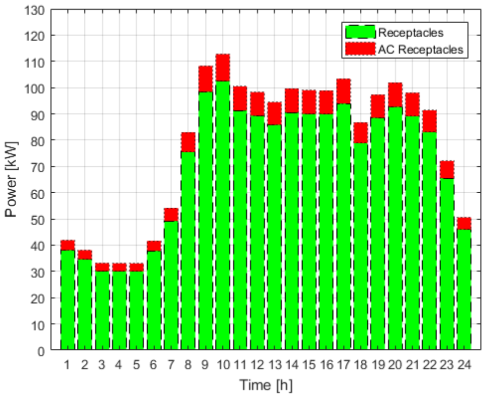


(c) Sunday fan power consumption

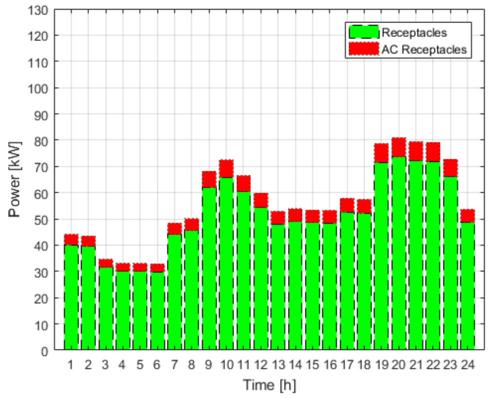
Figure 3.7: Ventilation fan load profiles for weekdays, Saturday and Sunday.

3.3.4 Receptacle Loads

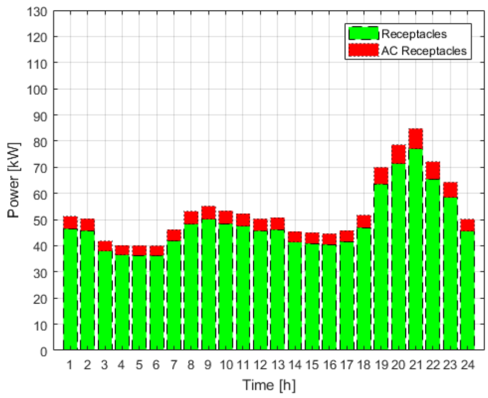
The receptacle loads follows the same activity schedules as seen in figure 3.4, in section 3.3.2. Due to the complexity of the wide composition of receptacle loads, an exact statement regarding power is hard to make. To determine the receptacle load power with great accuracy, one would need the combination and quantity of products together with the exact time each device is active. To approximate the receptacle load power in this report, the activity schedules mentioned above will be used together with an building performance rating method that state that the total receptacle power should be equal to 25% of the total load [41]. Notice that the total load refers to the total load of the entire building (all loads), in this case, it is assumed that the total load are the loads managed in this chapter. The result of this assumption can be seen in figure 3.8, where the receptacle power is displayed, for one weekday, Saturday and Sunday. As mentioned in section 2.3.4, 10% of the total receptacle loads are assumed to operate directly at 50Hz AC.



(a) Weekday receptacle consumption



(b) Saturday receptacle consumption

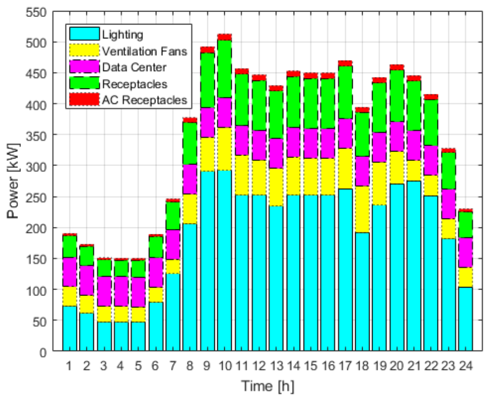


(c) Sunday receptacle consumption

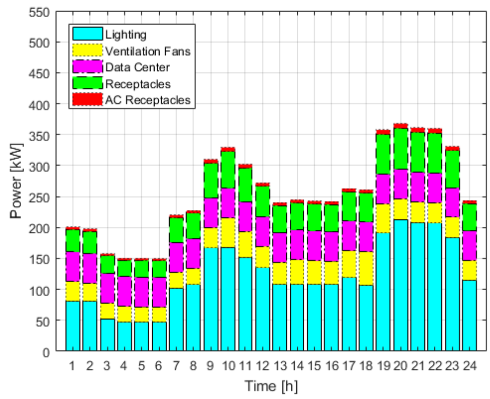
Figure 3.8: Receptacle load profiles for weekdays, Saturday and Sunday.

3.3.5 Load Profiles

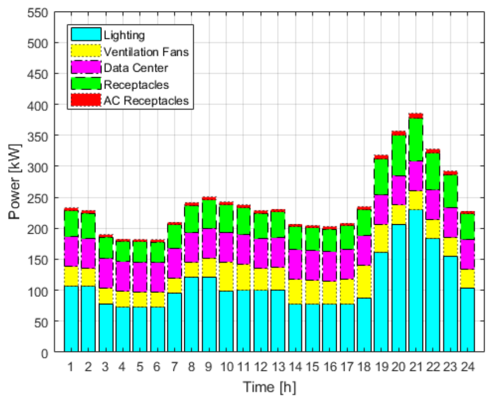
In figure 3.9, all examined loads are merged together, thus the figure illustrates the total load profiles for the medium load case as mentioned in section 3.3. These load profiles are a fusion of the loads illustrated in figures; 3.3, 3.5, 3.7 and 3.8. Note that the load profiles in figure 3.9 are unscaled, meaning these figures illustrate an ideal case with no corresponding losses. These load profiles will later be scaled, with efficiencies for the three different load cases, described in section 3.1.3.



(a) Total weekday load profile



(b) Total Saturday load profile



(c) Total Sunday load profile

Figure 3.9: Load profile for all examined loads during weekdays, Saturday and Sunday for the medium load case.

3.4 Theoretical Efficiencies

In the case of no information regarding efficiency for a specific product or conversion type, a theoretical obtained value will be used. These efficiencies can be seen in tables 3.4-3.8.

Table 3.4: AC/DC converter efficiency for devices rated less then 75W.

AC/DC Converter <75W	Efficiency [%]
Single-stage AC-DC flyback [25]	90.6

Table 3.5: AC/DC converter efficiency for devices rated greater or equal to 75W.

AC/DC Converter $\geq$ 75W	Efficiency [%]
Two-stage AC-DC flyback [25]	92.6
LLC resonant AC-DC [26]	94.5
Average value	93.55

Table 3.6: DC/DC converter efficiency for devices rated less then 75W.

DC/DC Converter <75W	Efficiency [%]
LLC DC/DC [25]	96.35

Table 3.7: DC/DC converter efficiency for devices rated greater or equal to 75W.

DC/DC Converter $\geq$75W	Efficiency [%]
Buck DC/DC [27]	98.3
Soft switching DC/DC [28]	96.0
Average value	97.15

Table 3.8: DC/AC inverter efficiency for devices rated greater or equal to 75W.

DC/AC Inverter $\geq$75W	Efficiency [%]
DC/AC [29][30]	95.0

3.5 Photovoltaic

The photovoltaic modules are producing DC, commonly there is an inverter to make AC out of the DC, either to be able to sell the energy to the grid or to supply internal loads. In a DC system there will be a DC/DC converter instead. The size of the photovoltaic installation is approximately 80kW. The installation will not consist of any energy storage units and will not be grid connected. The used solar module is *SunPower®E-Series E20-327*, which is a high efficiency module (η>20%), with a nominal power of 327W [43]. Information regarding the installation can be seen in table 3.9, the generation is simulated in *PVsyst*.

Table 3.9: Information regarding the photovoltaic installation in Platinan.

Installed Power	80.04 kW
Generation	876 kWh/kW,year
Total Generation	70 132 kWh/year

3.5.1 European Inverter Efficiency

Instead of looking at the inverter maximum efficiency point, which can give an unfair picture of the overall performance, one can use the European inverter efficiency (EIE), η_{EU}, providing a more just measurement of performance. EIE is based on the probability of different loadings of the inverter, this probability is weighted together with the inverter efficiency for that working point. The EIE weighting method formula is as follows

$$\eta_{EU} = 0.03\cdot\eta_{5\%}+0.06\cdot\eta_{10\%}+0.13\cdot\eta_{20\%}+0.10\cdot\eta_{30\%}+0.48\cdot\eta_{50\%}+0.20\cdot\eta_{100\%} \quad [\%]. \quad (3.2)$$

As seen in (3.2), the dominating loading point is at 50% of maximum load [39].

4

Base Verification

To be able to answer if there are potential energy savings due to DC distribution and DC customized loads a loss study must be carried out. The loss study will compare DC losses in the distribution system and in the loads with equivalent AC distribution system and loads. Later in this chapter the load profiles from section 3.3.5 are scaled with resulting efficiencies from this chapter and the loads are evaluated individually. This chapter also contains financial assumptions and used energy price.

4.1 Distribution Losses

To determine the distribution losses and the efficiency of the AC and DC distribution system, both hand calculations and simulations are performed. The hand calculations are based on equations from section 2.1 and use no real cable product parameters, while the simulation section use existing products. Due to this reason, the simulation result will be used to determine the final efficiency. Due to the large amount of installed power, as seen in section 3.3.5, the majority of the distribution system in Platinan consist of copper bars, these copper bars are assumed loss less in both AC and DC distribution case. Platinan have three shafts with distribution centrals at each floor, due to this, the necessary cable lengths becomes shortened in comparison to other projects. Thus, in this work, all distribution and installation is treated as three conductor cables, consisting of phase (L), neutral (N) and protective earth (PE), in both AC and DC case, in DC case the neutral conductor is referred to as M. One floor of the building have been taken into consideration, the resulting efficiency is being applied to the entire building.

4.1.1 Hand Calculations

Table 4.1 illustrates the calculated conductor parameters for copper at 50°C conductor temperature. To calculate the parameters in table 4.1, the equations from section 2.1 is used. The inductance, L, do not have any noticeable impact on the impedance, which gives the suspicion that the difference in current according to section 2.1.3 is the reason for difference in power loss between the AC and DC conductor. An example of difference in power loss can be seen in table 4.2.

Table 4.1: Cable parameters at 50°C, for copper conductors.

Cross-section, A $[mm^2]$	Resistance, R $[m\Omega/m]$	Inductance, L $[\mu H/m]$	Impedance, Z $[m\Omega/m]$
1.50	12.5	0.3692	12.5
2.50	7.50	0.3262	7.50
4.00	4.70	0.3020	4.70
6.00	3.10	0.2658	3.10
10.0	1.90	0.2512	1.90
16.0	1.20	0.2194	1.20
25.0	0.75	0.2166	0.75
35.0	0.53	0.2048	0.54
50.0	0.37	0.1912	0.38

Table 4.2: Example of receptacle load distribution efficiency for AC and DC.

Load	Area $[mm^2]$	Type	Voltage [V]	Current [A]	Length [m]	Power Loss [W]	Efficiency [%]
Receptacle	1.50	AC	230	10.0	10	12.5	99.5
Receptacle	1.50	DC	380	6.1	10	4.65	99.8

In figure 4.1, the power loss for a 1.5mm^2 installation cable is illustrated. The two data cursors in the figure marks the maximum allowed length of the cables to still satisfy the ≤2% power loss, at 50°C. The AC cable can be approximate 14m and the DC cable can be approximate 38m.

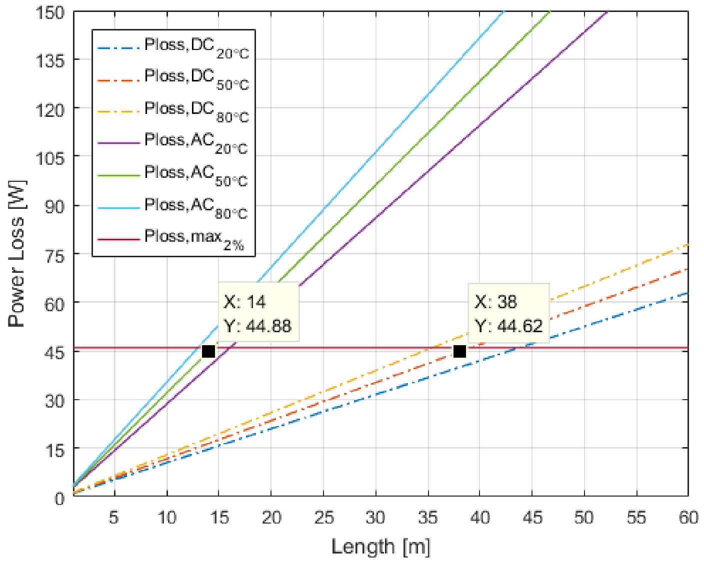


Figure 4.1: Power loss for a 1.5mm^2 cable, for AC and DC. Three cases of conductor temperature, 20°C, 50°C and 80°C respectively. The red line indicates maximum allowed losses, which in this case is 2%.

4.1.2 FEBDOK Simulations

As a complement to the hand calculations, a software program called *FEBDOK* was used, which has the ability to calculate voltage drop among other calculations. The advantage of FEBDOK is the many parameters the program takes into account, which otherwise are neglected when calculating by hand. Figure 4.2 illustrates how the virtual environment appears like, showing one bus with three load branches, illustrating cable length, type of cable and load type.

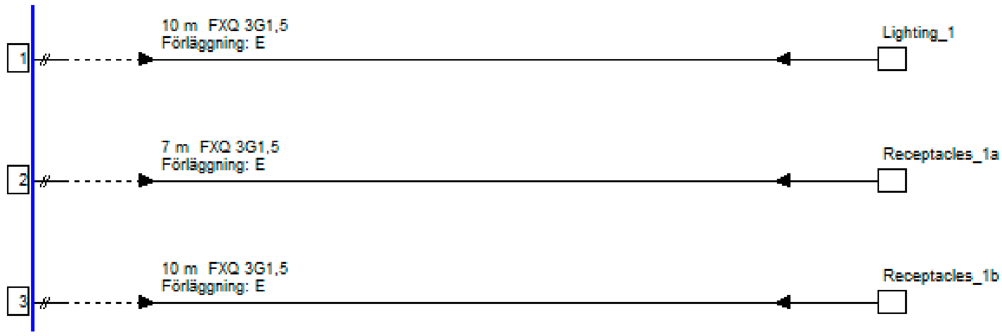


Figure 4.2: One bus with three load branches, in FEBDOK simulation program environment.

In table 4.3, the result of the loads in figure 4.2 together with a ventilation load are illustrated, both for AC and DC. As seen in table 4.3, the difference in efficiency, $\Delta\eta$, between AC and DC is <1% for each branch. So basically what determines the total efficiency is the number of series-connected branch-stages. The more there are, the more it would gain the DC distribution system. As mentioned in section

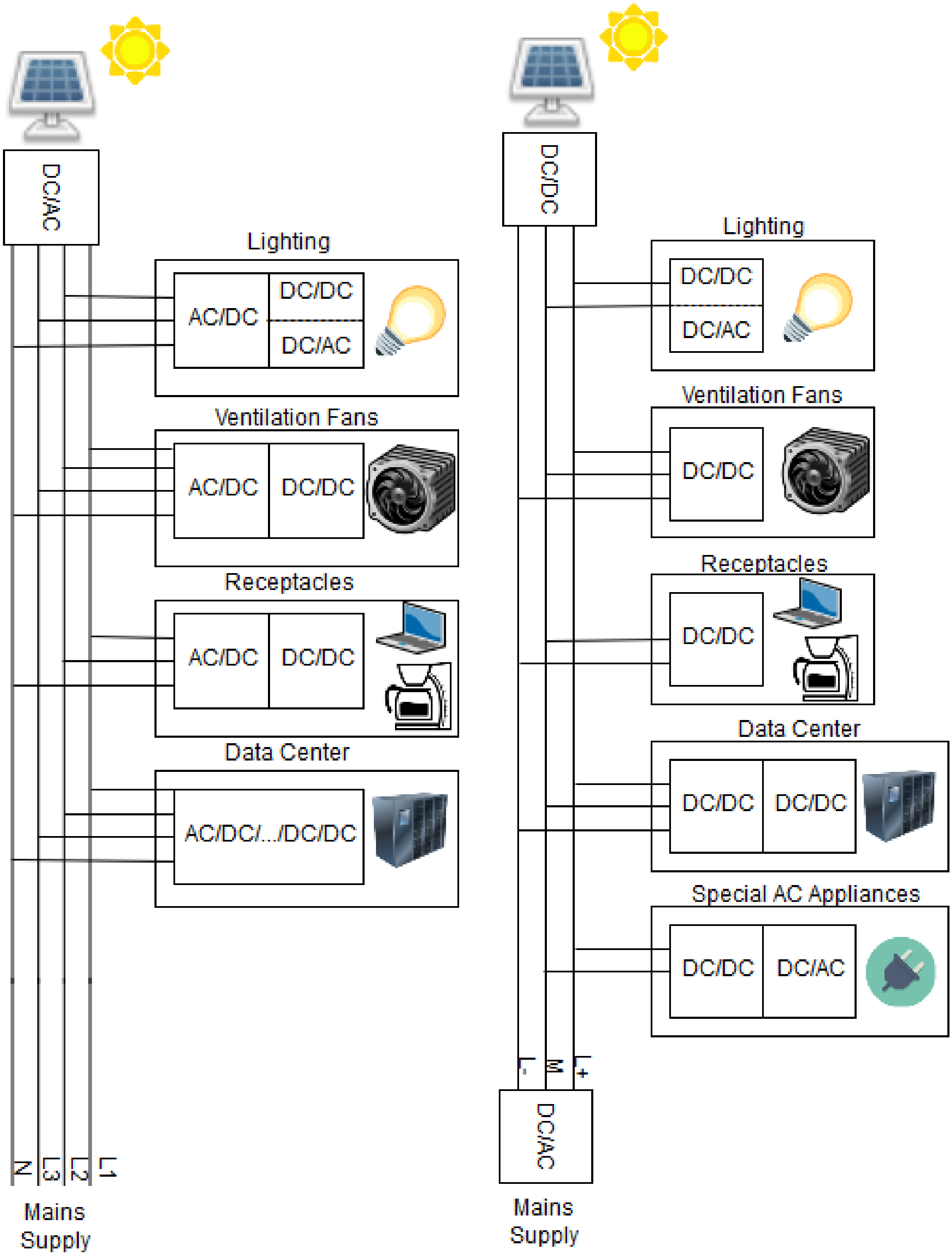
4.1, due to the large part of the distribution system consists of copper bars, the distribution system is not as profitable as it could be, leading to a lower, $\Delta\eta$. The final efficiency used for AC, $\eta_{AC} = 97.9\%$ and for DC and DC$_{opt}$, $\eta_{DC} = \eta_{DC_{opt}} = 99.2\%$. Leading to an efficiency improvement, $\Delta\eta = 1.3\%$. This corresponds well with other reported results regarding difference in efficiency, between AC and DC distribution systems [31].

Table 4.3: FEBDOK simulation parameters and results, showing the efficiency for each specific branch.

Load	Area [mm^2]	Type	Voltage [V]	Current [A]	Length [m]	Power Loss [W]	Efficiency [%]
Receptacle 1a	1.50	AC	230	10.0	10	20.3	99.1
Receptacle 1b	1.50	AC	230	10.0	7	29.0	98.7
Lighting	1.50	AC	230	8.70	10	21.9	98.9
Ventilation	6.00	AC	230	13.0	30	39.8	98.7
Receptacle 1a	1.50	DC	380	6.1	10	7.4	99.6
Receptacle 1b	1.50	DC	380	6.1	7	10.6	99.5
Lighting	1.50	DC	380	5.3	10	8.0	99.6
Ventilation	6.00	DC	380	7.9	30	14.7	99.5

4.2 Conversion Efficiency Determination

It is no secret that energy conversions between AC to DC and vice-versa results in losses, that much is already discussed. Not all, but many of our everyday electrical devices already use DC, thus the number of conversion stages could be reduced if using DC as utility voltage. Keep in mind though, that there will be an additional rectification stage from AC to DC between the grid supply AC voltage and the DC distribution system inside the building. This extra rectification loss needs to be considered when comparing the two systems. In figure 4.3, a potential AC and DC distribution system is illustrated. Note that figure 4.3 is an illustration of a possible principle and not an exact schedule regarding the supply voltage levels (phases). In the following chapter each load will be investigated and for most loads practical measurements are carried out. In case of measurement, the measurement object is firstly provided with AC and secondly with DC. Thirdly, DC$_{opt}$ will be the efficiency with DC as supply voltage minus the losses occurring due to rectification. It is assumed that all losses not occurring in the DC/DC stage is due to rectification.



(a) Typical AC distribution grid layout

(b) Examined DC distribution gird layout

Figure 4.3: AC and DC distribution system layouts, illustrating; loads, conductors and the conversion steps for the two systems. Please note that protective earth (PE) conductor is not present in this illustration [6].

4.2.1 Data Center

The AC and DC data center layout compared in this report are the ones from section 2.3.1, figure 2.10 and figure 2.11. To be able to state the overall potential efficiency improvements of the DC system, the efficiency needs to be determined for the devices along the power path. The AC system power path consists of: AC UPS, wiring, PDU and PSU as seen in 2.10. The DC system power path consists of: DC UPS, wiring and PSU as seen in 2.11. Cooling devices power and efficiency are not considered in the comparison, although there is reason to believe that if DC data center have higher efficiency (lower losses), less heat is produced and the need for cooling decreases. It is more common in the US that the PDU contains a transformer, in this report the PDU will be considered transformerless and loss less [21]. Efficiencies of both AC UPS and DC UPS can be seen in table 4.4, keep in mind that there is a wide selection of UPSs on the market, with varying efficiencies. If there is no product efficiency information for a certain work point, a nearby work point efficiency will be used.

Table 4.4: UPS efficiency for different load cases.

UPS model (manufacturer)	Load [%]			
	25	50	75	100
AC: APC Symmetra PX (Schneider) [32]	93.0%	95.0%	95.0%	95.0%
AC: PowerWave 33 (ABB) [33]	95.8%	96.1%	96.0%	95.6%
DC: Theoretical DC/DC	97.15%	97.15%	97.15%	97.15%
AC Average Efficiency:	94.4%	95.6%	95.5%	95.3%
DC Average Efficiency:	97.15%	97.15%	97.15%	97.15%

As seen in table 4.4 there is a slight percentage advantage for DC UPSs for all load points. Keep in mind that a different selection of products could present a different result. The wiring-losses for the data center will be considered to increase linearly with the load, starting at 0% at zero load, 0.5% at 50% load and peaking at 1% at 100% of the maximum load, thus in many cases distribution wiring losses is negligible in data centers [21]. In figure 4.5, the efficiency for AC and DC power supply units can be seen, for different load cases.

Table 4.5: PSU efficiency for different load cases.

PSU model (manufacturer)	Load [%]		
	20	50	80
AC Input: 230V (Cisco, Dell, IBM, Lenovo) [38]	90.0%	94.0%	91.0%
DC Input: 350-430V (Delta) [19]	89.8%	95.6%	96.2%

In table 4.6 below, the overall system efficiency is presented, for load cases equal to 20%, 50% and 80% of maximum load. As seen, there is an increasingly overall efficiency improvement for the DC data center, increasing further for the high load cases.

Table 4.6: Overall system efficiency for AC and DC data center at load points equal to 25%, 50% and 100% of maximum load.

Load	UPS		Wiring		PSU		Overall Efficiency
$AC_{20\%}$	94.4%	·	99.8%	·	90.0%	=	84.8%
$DC_{20\%}$	97.15%	·	99.8%	·	89.8%	=	87.1%
$AC_{50\%}$	95.6%	·	99.5%	·	94.0%	=	89.4%
$DC_{50\%}$	97.15%	·	99.5%	·	95.6%	=	92.4%
$AC_{80\%}$	95.5%	·	99.2%	·	91.0%	=	86.2%
$DC_{80\%}$	97.15%	·	99.2%	·	96.2%	=	92.7%

4.2.2 Lighting

As seen in figure 4.3, the lighting source can use either DC or AC in its final stage. This is, as mentioned in section 2.3.2, due to what kind of light source used, where LED uses DC and fluorescent tubes uses AC. In this report all lighting will be assumed to use LED technology, as mentioned earlier. The efficiency of the lighting category is determined using an experimental measurement. The measurement is carried out based on the principle that the rectifier bridge can be fed with DC as well, as mentioned in section 3.2. The LED-driver which was used for measurement was a *MALMBERGS SLT30-12VLG-Es* [45], which has a power rating of 30W. In figure 4.4, the principle of the measurement setup is illustrated. Where both input and output power is measured to determine the efficiency of the drive. All measurements were carried out using a power meter capable of measuring transients at 50Hz, when using AC as supply voltage.

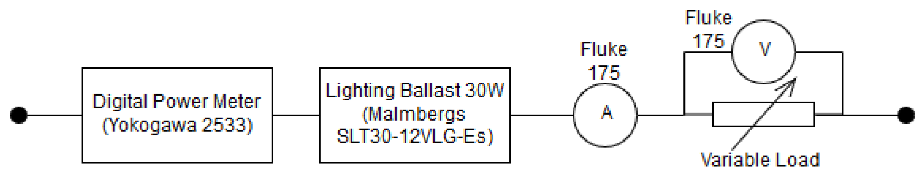


Figure 4.4: Principle sketch of measurement setup for the LED-drive.

The LED-drive different loading points were obtained by using a variable load to sweep through the work interval of the driver. The measurement result obtained, is shown in figure 4.5, which indicates an efficiency improvement for both DC and DC_{opt} solution, compared to the standard AC case.

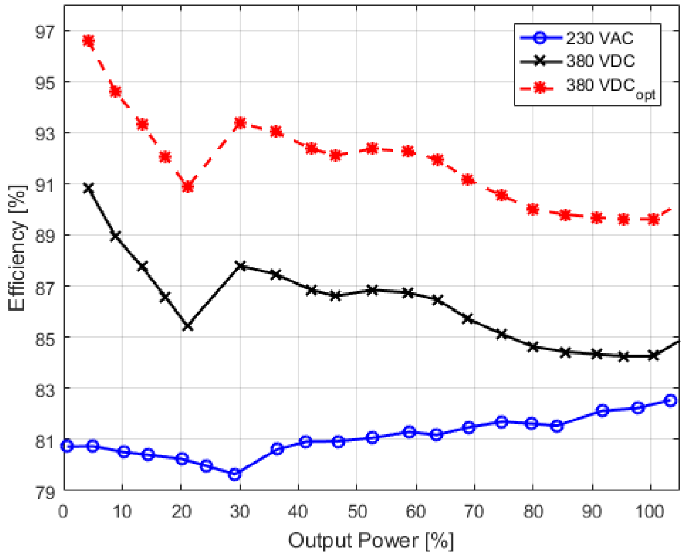


Figure 4.5: Measured LED-drive efficiency, based on supply voltage type.

4.2.3 Ventilation Fans

The used fan motor was an *EC K3G190-RC05-03* [46], which is an electrically commutated permanent magnet motor, with a rated power of 83W. In contrary to the LED-drive measurement, the output power was not measured. Instead the speed of the motor were monitored and the efficiency is given as the difference in needed supply power to achieve a certain motor speed. The principle of the fan motor measurement is illustrated in figure 4.6. Where the motor speed is monitored through the motors tachometer output, which sends one pulse for each revolution. In addition to the supply voltage, an external DC voltage supply unit were used to control the speed of the motor, sending a control voltage signal between 1-10V.

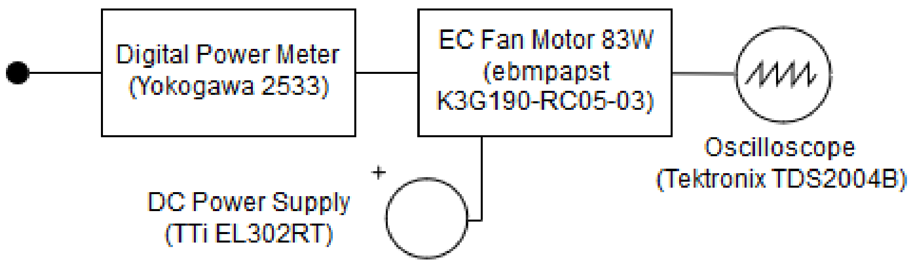


Figure 4.6: Principle sketch of the fan motor measurement setup.

The measurement result can be seen in figure 4.7. The load points are based on motor speed, instead of input power. It can be seen that DC$_{opt}$ overall reaches any specific speed at lowest input power and that the AC case in a majority of the interval requires the most power to achieve the same speed.

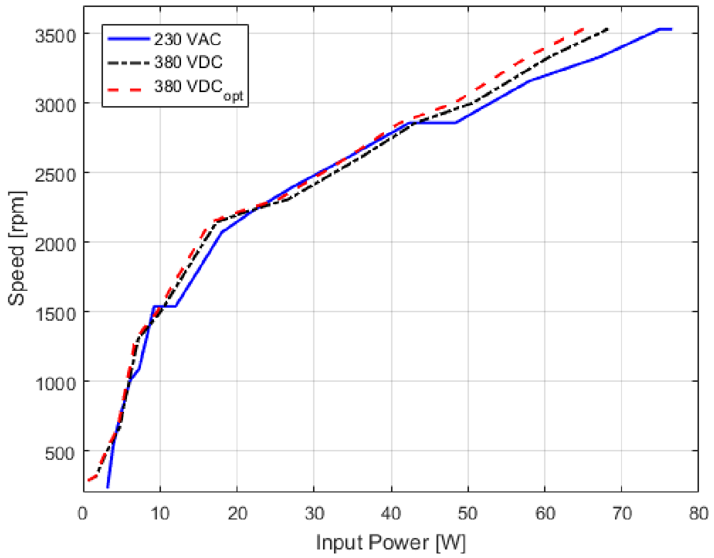


Figure 4.7: Ventilation fan fed with different supply voltages.

4.2.4 Receptacle Loads

As seen in table 2.1 from section 2.3.4, there are many different types of receptacle loads. Due to unknown quantities and efficiencies, this load category will be simplified to one products efficiency, namely a laptop-charger. The measurement was carried out on laptop-charger, the procedure was much alike the LED-driver one. Where input and output power were measured. The measurement object was a laptop-charges of model *ACER PA-1900-32* [47]. with rated power of 90W. The principle of the measurement setup can be seen in figure 4.8.

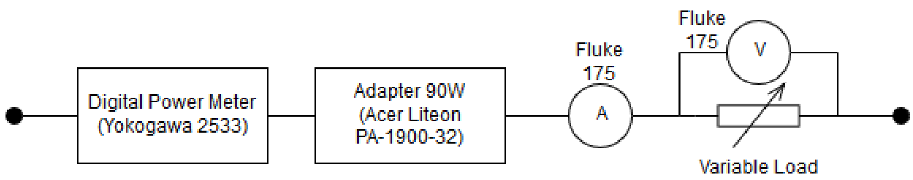


Figure 4.8: Principle sketch of the laptop-charger measurement setup.

Measurement results illustrated in figure 4.9 shows that for the majority of the load points DC is superior to AC. DC$_{opt}$ is at all points more efficient than the other two cases. In figure 4.10, a picture of the experimental measurement setup can be seen, furthest to the right is the DC voltage supply unit feeding the power meter which measures the input power to the laptop-charger, which is visible on the table. To the left in the picture there are two multimeter's measuring voltage and current, in between them is the variable loads.

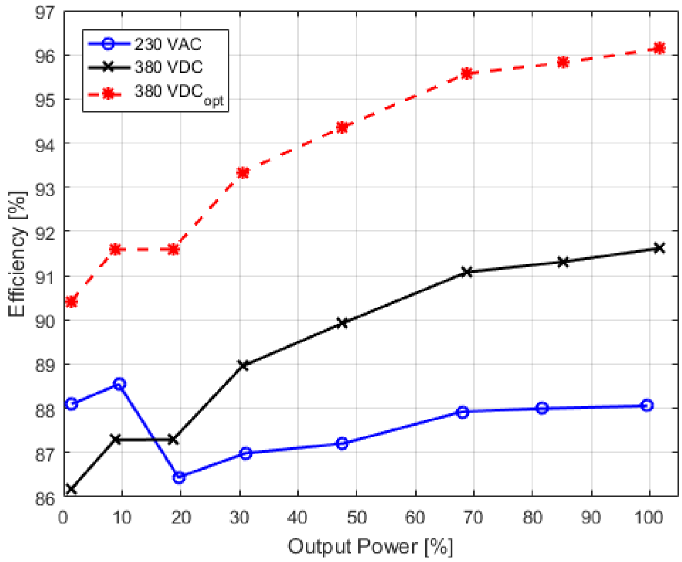


Figure 4.9: Measured laptop-charger efficiency, based on supply voltage type.

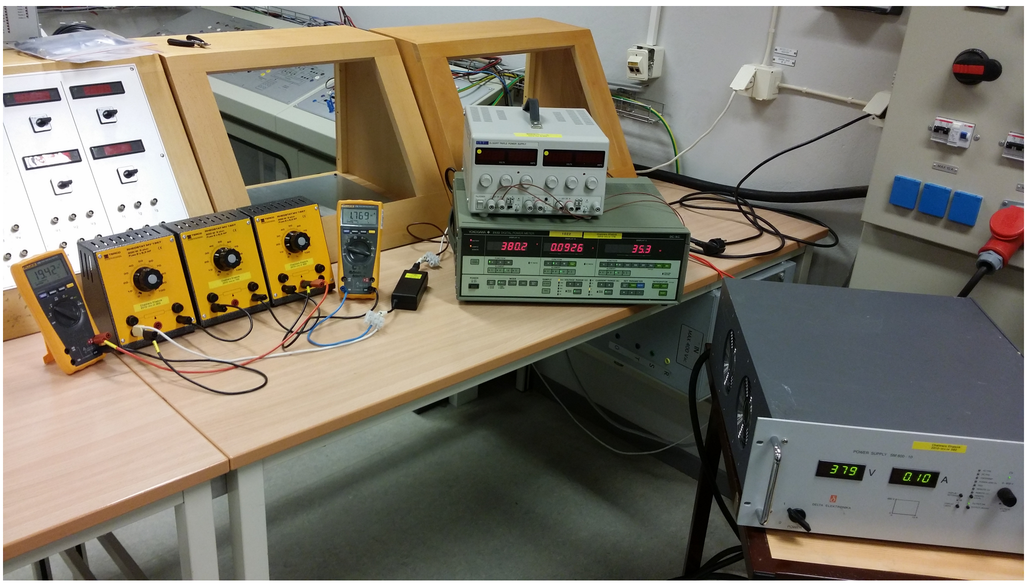


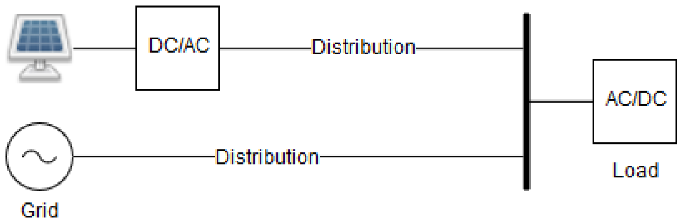
Figure 4.10: Picture from experimental measurements carried out on a laptop-charger.

4.2.5 Special AC Appliances

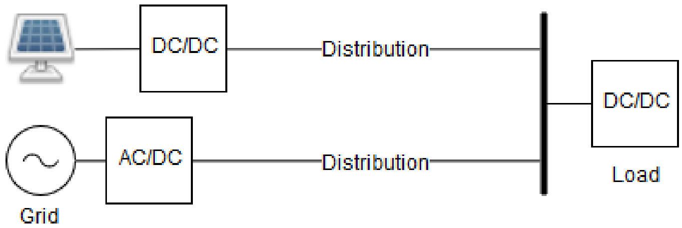
In figure 4.3, it is possible to feed the *Special AC Appliances* from AC supply mains, before the mains rectification. This would then require a parallel AC distribution grid along with the DC distribution grid. Due to the size of the grid infrastructure and the relatively low power consumption of the special AC appliances, according to section 2.3.4, the parallel distribution systems is not an approach covered in this report. The AC appliances are thus in some term double-punished, firstly due to the mains rectification and secondly due to the inversion process close to the end-usage.

4.2.6 Photovoltaic

In figure 4.11a and 4.11b, the AC and DC photovoltaic installation can be seen respectively. In this section, only the photovoltaic part is evaluated, not the fact that the grid supply needs to be rectified for the DC case.



(a) AC layout



(b) DC layout

Figure 4.11: AC and DC photovoltaic installation setup, with grid supply included.

In table 4.7, efficiencies for the inverter used in the AC case and converter used in the two DC cases are illustrated together with distribution and a load in form of receptacles. Depending on what load to supply, the start-to-end efficiency will differ, the finalized photovoltaic installation efficiency only take conversion and distribution efficiency into account.

Table 4.7: Efficiency for photovoltaic installation in AC and the two DC cases.

Component	Efficiency [%]		
	AC	DC	DC_{opt}
Inverter/Converter	95.0	97.15	97.15
Distribution	97.9	99.2	99.2
Load (Receptacles)	87.4	90.1	94.6
Total	81.3	86.3	91.7

4.3 Mains Rectification

As seen in figure 4.3, the main voltage needs to be rectified to enable DC as distribution voltage. This is done by using several rectification cabinets, consisting of smaller rectification modules. Figure 4.12, illustrates a potential method for the main rectification. This configuration consist of six cabinets with the possibility to rectify 135kW each. Each cabinet consist of 54 modules with the rectification capability of 2.5kW each. This solution is flexible, it is possible to add additional cabinets or to change number of modules in cabinet, although 54 is the maximum number of modules per cabinet [36]. When gathering the entire rectification process this close, it enables monitoring and control mechanics, non of which will be considered in this work. Another advantage with centralizing the rectification is the possibility to achieve higher efficiency rectifier modules by choice. End product loads rectifiers is chosen to fulfill potential requirements but still yield maximum profit for manufacturers. In figure 4.13, the efficiency of one 2.5kW rectifier module is illustrated. This measurement is made with 350 VDC as output voltage, an assumption that the same efficiency is obtainable with 380 VDC is made. The black solid curve shows the efficiency with 230 VAC as input voltage, the red dashed curve shows the efficiency with modified input voltage to 265 VAC, which is done for the DC_{opt} solution. This measurement is not self-performed, but the principle is the same as with the previous mentioned measurements. Input and output power are measured to obtain the efficiency of the rectifier module. The same module can be used for the two different input voltages, this is done by tuning the rectifier to a specific input voltage.

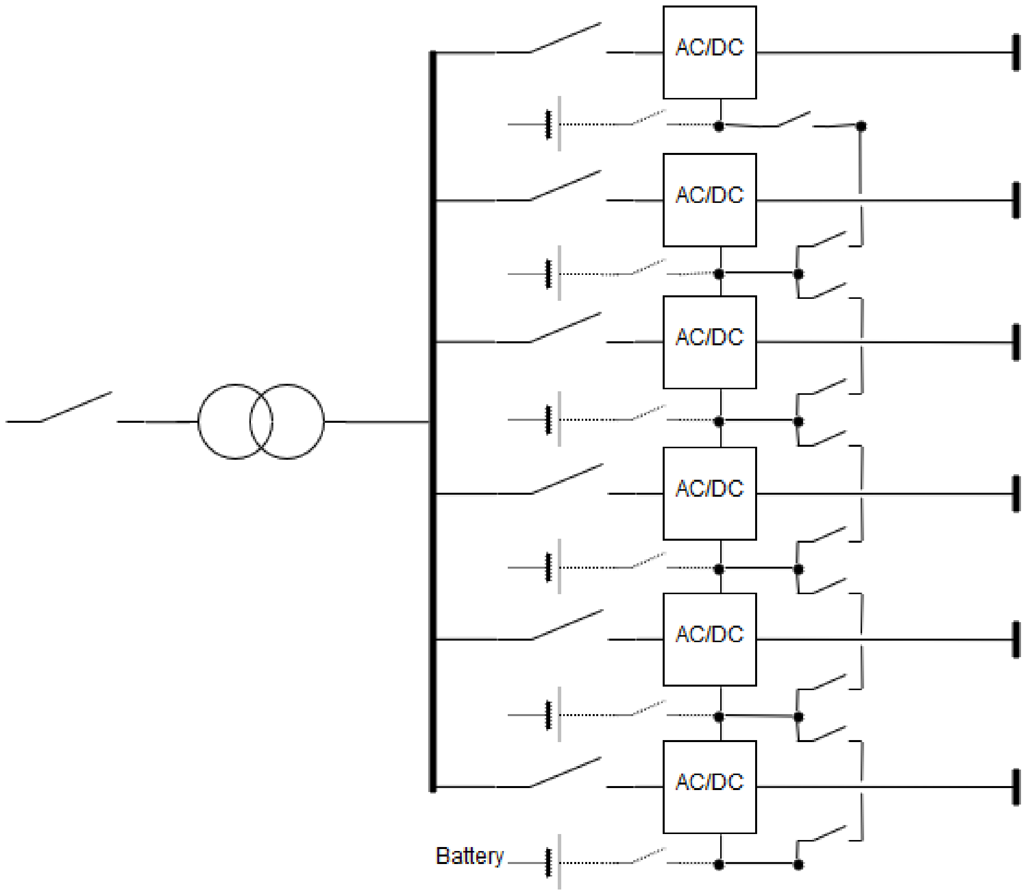


Figure 4.12: Potential mains rectification principle.

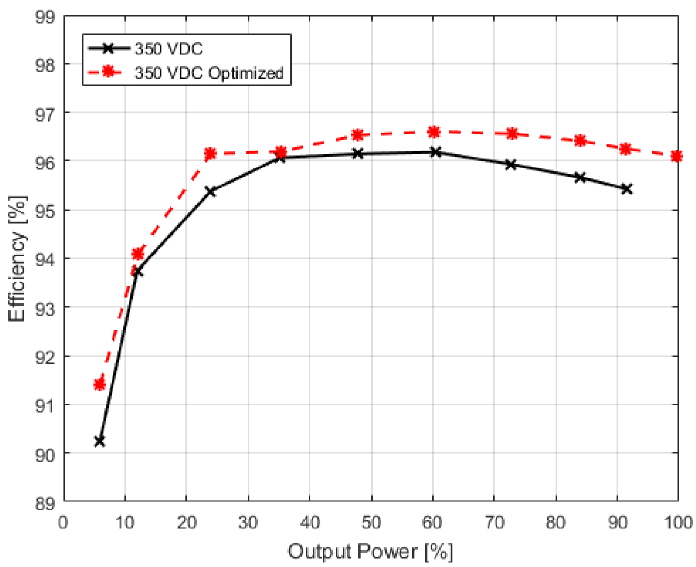


Figure 4.13: Mains rectification efficiency for a 2.5kW module, used for DC and DC_{opt} [37].

4.4 Load Cases

The load profiles illustrated in figure 3.9, are as mentioned the needed energy to be provided in a loss less ideal case. Since there will be losses, on the path from supply to end use, as described in chapter 4, the supplied energy will be higher than the energy consumed by the loads. This difference in supplied energy is to be compared between the AC and the two DC systems. This difference will be investigated for load cases defined in section 3.1. Each load case is scaled with its corresponding efficiencies respectively and the cases are weighted together based on probability, to provide total annual energy consumption. Finally, the difference in energy consumption between AC-DC and AC-DC$_{opt}$ are summarized to see if there is any savings in energy, both hourly and annually.

4.4.1 Load Demand Case Efficiencies

In table 4.8 the low demand case efficiencies for each load can be seen. Each of these efficiencies are applied to figure 3.9, to get the true value of the needed energy to supply the loads. As seen in table 4.8, low demand case corresponds to 20% of maximum load. It can be see that for the *Ventilation Fan* category, the efficiency in the AC case is set as reference, and that the DC case efficiency is lower, hence needed to supply more power. It can also be seen that for categories *AC Receptacles* and *Mains Rectification*, the efficiency for AC case is 100%, since none of these categories are present in an AC solution. In a similar way, table 4.9 which corresponds to 50% load case and table 4.10 which corresponds to 80% load case are both respectively applied to the load profiles.

Table 4.8: Low load demand scaling efficiencies for the AC, DC and DC$_{opt}$ case respectively.

Load (20%)	System Efficiency [%]		
	AC	DC	DC$_{opt}$
Data Center	84.8	87.1	87.1
Lighting	80.2	85.4	90.9
Ventilation Fans	100.0	95.3	100.0
Receptacles	86.4	87.3	91.1
AC Receptacles	100.0	95.0	95.0
Distribution	97.9	99.2	99.2
Mains Rectification	100.0	94.8	95.5

Table 4.9: Medium load demand scaling efficiencies for the AC, DC and DC_{opt} case respectively.

Load (50%)	System Efficiency [%]		
	AC	DC	DC_{opt}
Data Center	89.4	92.4	92.4
Lighting	81.1	86.8	92.4
Ventilation Fans	100.0	111.0	115.1
Receptacles	87.4	90.1	94.6
AC Receptacles	100.0	95.0	95.0
Distribution	97.9	99.2	99.2
Mains Rectification	100.0	96.1	96.6

Table 4.10: High load demand scaling efficiencies for the AC, DC and DC_{opt} case respectively.

Load (80%)	System Efficiency [%]		
	AC	DC	DC_{opt}
Data Center	86.2	92.7	92.7
Lighting	81.5	84.4	89.8
Ventilation Fans	100.0	97.9	102.9
Receptacles	88.0	91.5	96.0
AC Receptacles	100.0	95.0	95.0
Distribution	97.9	99.2	99.2
Mains Rectification	100.0	95.7	96.5

4.4.2 Weighted Energy Demand

When the efficiencies from section 4.4.1 have been applied, the next step is to find the difference in energy demand between the solutions. This is made using (4.1)-(4.6), the result is a difference term in needed energy, ΔE, on an hourly basis. This difference for weekdays can be seen in figure 4.14.

$$\Delta E_{weekday,DC,low} = E_{weekday,AC,low} - E_{weekday,DC,low} \tag{4.1}$$

$$\Delta E_{weekday,DC_{opt},low} = E_{weekday,AC,low} - E_{weekday,DC_{opt},low} \tag{4.2}$$

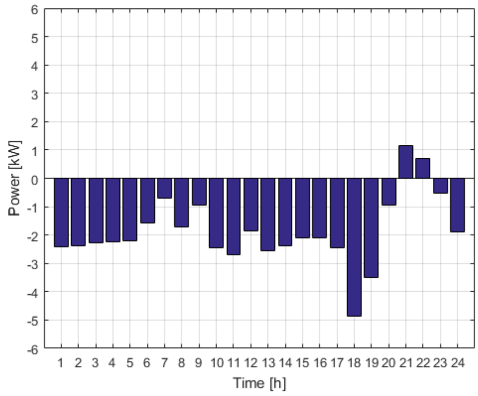
$$\Delta E_{weekday,DC,medium} = E_{weekday,AC,medium} - E_{weekday,DC,medium} \tag{4.3}$$

$$\Delta E_{weekday,DC_{opt},medium} = E_{weekday,AC,medium} - E_{weekday,DC_{opt},medium} \tag{4.4}$$

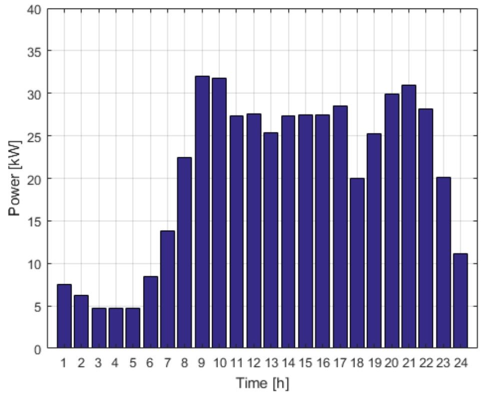
$$\Delta E_{weekday,DC,high} = E_{weekday,AC,high} - E_{weekday,DC,high} \tag{4.5}$$

$$\Delta E_{weekday,DC_{opt},high} = E_{weekday,AC,high} - E_{weekday,DC_{opt},high} \tag{4.6}$$

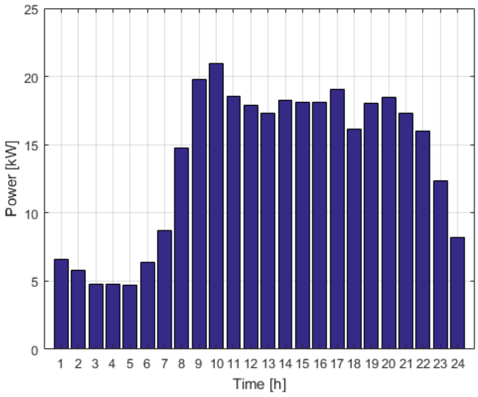
The same equations are used to determine the difference in energy demand for Saturday and Sunday respectively, resulting in a total of 18 equations.



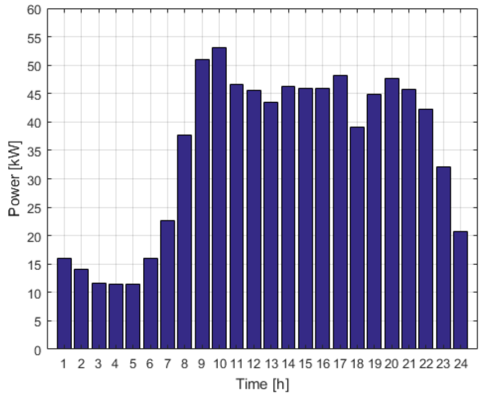
(a) Low Load Weekday: AC-DC



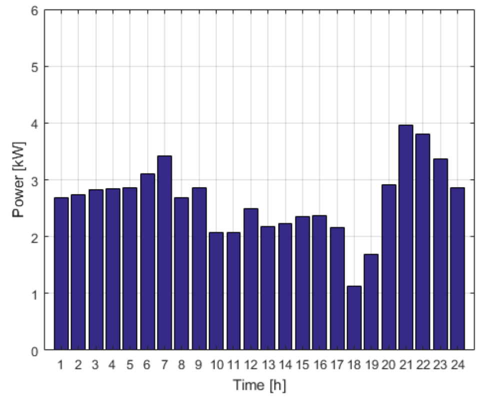
(b) Low Load Weekday: AC-DC$_{opt}$



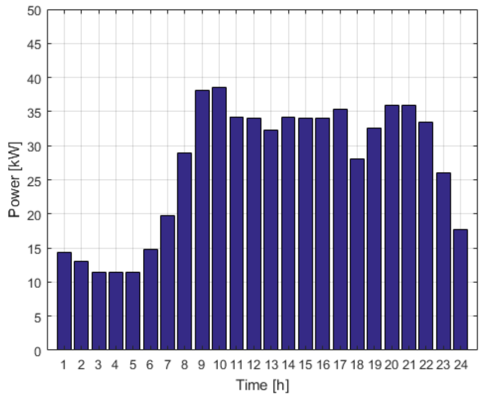
(c) Med Load Weekday: AC-DC



(d) Med Load Weekday: AC-DC$_{opt}$



(e) High Load Weekday: AC-DC



(f) High Load Weekday: AC-DC$_{opt}$

Figure 4.14: Difference in needed energy supply between AC and DC and AC and optimized DC.

The summarized energy from figure 4.14, between hours 1-24 can be seen in table 4.11. The table shows that for 20% of maximum load and for a weekday, the DC solution provides a negative number of approximately -45kWh, which means that for this load case, the AC solution is more beneficial. On the contrary, for the same load case the optimized DC solution provides an energy saving of approximately 493kWh during one weekday for the low demand case.

Table 4.11: Difference in energy demand compared to the AC system. Negative values implies that standard AC solution is more beneficial.

Load	Type	$\Delta E_{weekday}$[kWh]	$\Delta E_{saturday}$[kWh]	ΔE_{sunday}[kWh]
Low	DC	-44.9	993.1	-45.9
20%	DC_{opt}	492.9	1355.9	287.8
Medium	DC	331.1	226.9	210.3
50%	DC_{opt}	839.5	573.1	529.3
High	DC	63.7	-951.5	68.2
80%	DC_{opt}	649.8	-544.7	445.2

Inserting values from table 4.11 into (4.7), (4.8) and (4.9) gives

$$\begin{gathered}\Delta E_{(weighted,low)/year} = n_{days/year} \cdot \\ [\Delta E_{weekday,low}(5/7) + \Delta E_{saturday,low}(1/7) + \Delta E_{sunday,low}(1/7)]\end{gathered} \tag{4.7}$$

$$\begin{gathered}\Delta E_{(weighted,medium)/year} = n_{days/year} \cdot \\ [\Delta E_{weekday,medium}(5/7) + \Delta E_{saturday,medium}(1/7) + \Delta E_{sunday,medium}(1/7)]\end{gathered} \tag{4.8}$$

$$\begin{gathered}\Delta E_{(weighted,high)/year} = n_{days/year} \cdot \\ [\Delta E_{weekday,high}(5/7) + \Delta E_{saturday,high}(1/7) + \Delta E_{sunday,high}(1/7)]\end{gathered} \tag{4.9}$$

resulting in table 4.12. This is done for DC, DC_{opt} and for a weekday, Saturday and Sunday.

Table 4.12: Difference in energy demand over one year for the three load case, with weekdays, Saturdays and Sundays weighted together.

$\Delta E_{(weighted,low)/year}$	DC	37 683.6 kWh/year
	DC_{opt}	214 213.3 kWh/year
$\Delta E_{(weighted,medium)/year}$	DC	109 119.4 kWh/year
	DC_{opt}	276 351.9 kWh/year
$\Delta E_{(weighted,high)/year}$	DC	-29 450.3 kWh/year
	DC_{opt}	164 223.9 kWh/year

Together (4.7), (4.8) and (4.9) forms

$$\Delta E_{(weighted,total)/year} = \Delta E_{(weighted,low)/year} \cdot (x) + \Delta E_{(weighted,medium)/year} \cdot (y) + \Delta E_{(weighted,high)/year} \cdot (z) \tag{4.10}$$

where x, y and z represents the probability of that specific load case to occur. The sum of x, y and z equals one, representing 100% of the time. In table 4.12, the values represent 100% of the time for that specific load case. Thus, the medium load case is the most profitable for both DC and DC$_{opt}$. This work will take the least and most beneficial load distribution into consideration, using (4.10).

4.5 Individual Load Evaluation

Tables 4.13-4.17 illustrate the efficiency for each load individually, for the three different load cases from start to finish within the building. They also illustrates the difference in efficiency, $\Delta\eta$, between the two DC solutions and the AC reference system.

Table 4.13: Data center system efficiency and efficiency difference, $\Delta\eta$.

System Load	Efficiency [%]				
	Mains Rectification	Distribution	Conversions	Total	$\Delta\eta$
AC$_{20\%}$	100	97.9	84.8	83.0	-
DC$_{20\%}$	94.8	99.2	87.1	81.9	-1.1
DC$_{opt,20\%}$	95.5	99.2	87.1	82.5	-0.5
AC$_{50\%}$	100	97.9	89.4	87.5	-
DC$_{50\%}$	96.1	99.2	92.4	88.1	0.6
DC$_{opt,50\%}$	96.6	99.2	92.4	88.5	1.0
AC$_{80\%}$	100	97.9	86.2	84.4	-
DC$_{80\%}$	95.7	99.2	92.7	88.0	3.6
DC$_{opt,80\%}$	96.5	99.2	92.7	88.7	4.3

Table 4.14: Lighting system efficiency and efficiency difference, $\Delta\eta$.

System Load	Efficiency [%]				
	Mains Rectification	Distribution	Conversions	Total	$\Delta\eta$
$AC_{20\%}$	100	97.9	80.2	78.5	-
$DC_{20\%}$	94.8	99.2	85.4	80.3	1.8
$DC_{opt,20\%}$	95.5	99.2	90.9	86.1	7.6
$AC_{50\%}$	100	97.9	81.1	79.4	-
$DC_{50\%}$	96.1	99.2	86.8	82.7	3.3
$DC_{opt,50\%}$	96.6	99.2	92.4	88.5	9.1
$AC_{80\%}$	100	97.9	81.5	79.8	-
$DC_{80\%}$	95.7	99.2	84.4	80.1	0.3
$DC_{opt,80\%}$	96.5	99.2	89.8	85.9	6.1

Table 4.15: Ventilation fan system efficiency and efficiency difference, $\Delta\eta$.

System Load	Efficiency [%]				
	Mains Rectification	Distribution	Conversions	Total	$\Delta\eta$
$AC_{20\%}$	100	97.9	100	97.9	-
$DC_{20\%}$	94.8	99.2	95.3	89.6	-8.3
$DC_{opt,20\%}$	95.5	99.2	100	94.7	-3.2
$AC_{50\%}$	100	97.9	100	97.9	-
$DC_{50\%}$	96.1	99.2	111	105.8	7.9
$DC_{opt,50\%}$	96.6	99.2	115.1	106.9	9.0
$AC_{80\%}$	100	97.9	100	97.9	-
$DC_{80\%}$	95.7	99.2	97.9	92.9	-5
$DC_{opt,80\%}$	96.5	99.2	102.9	98.5	-0.6

Table 4.16: Receptacle system efficiency and efficiency difference, $\Delta\eta$.

System Load	Efficiency [%]				
	Mains Rectification	Distribution	Conversions	Total	$\Delta\eta$
$AC_{20\%}$	100	97.9	86.4	84.6	-
$DC_{20\%}$	94.8	99.2	87.3	82.1	-2.5
$DC_{opt,20\%}$	95.5	99.2	91.1	86.3	1.7
$AC_{50\%}$	100	97.9	87.4	85.6	-
$DC_{50\%}$	96.1	99.2	90.1	85.9	0.3
$DC_{opt,50\%}$	96.6	99.2	94.6	90.7	5.1
$AC_{80\%}$	100	97.9	88.0	86.2	-
$DC_{80\%}$	95.7	99.2	91.5	86.9	0.7
$DC_{opt,80\%}$	96.5	99.2	96.0	91.9	5.7

Table 4.17: AC receptacle system efficiency and efficiency difference, $\Delta\eta$.

System Load	Efficiency [%]					
	Mains Rectification	Distribution	Inversion	Conversions	Total	$\Delta\eta$
$AC_{20\%}$	100	97.9	100	86.4	84.6	-
$DC_{20\%}$	94.8	99.2	95.0	87.3	78.0	-6.6
$DC_{opt,20\%}$	95.5	99.2	95.0	91.1	82.0	-2.6
$AC_{50\%}$	100	97.9	100	87.4	85.6	-
$DC_{50\%}$	96.1	99.2	95.0	90.1	81.6	-4.0
$DC_{opt,50\%}$	96.6	99.2	95.0	94.6	86.1	0.5
$AC_{80\%}$	100	97.9	100	88.0	86.2	-
$DC_{80\%}$	95.7	99.2	95.0	91.5	82.5	-3.7
$DC_{opt,80\%}$	96.5	99.2	95.0	96.0	87.3	1.1

4.6 Economy

It is assumed that the cost of AC loads and equivalent DC loads are the same. Meaning LED-drives and laptop-chargers made without rectifiers and thereby suitable for DC_{opt} have the same cost as ordinary AC equipment. The same is assumed for photovoltaic inverters and like-sized DC/DC converters. The cost of AC cables is assumed to be equivalent to the cost of DC cables. No interest rate have been used, resulting in a linear payback. The function of all equipment have been assumed to be continuous, thus no regard of degradation has been taken into consideration. It has been assumed that the energy price is constant during the entire life-time of the equipment and payback-time. The energy price is further discussed in section 4.6.1. The photovoltaic installations payback-time is not investigated, but the financial savings based on AC or DC system are investigated. The rectification cabinets mentioned in section 4.3, cost approximately €30 000 each, depending on surveillance and battery-outlet options. Thus, the total cost of the six cabinets is €180 000, this is the only cost which is assumed to be purely belonging to the DC installation and thus is needed to be paid off. Due to the above assumption, the DC solution and the DC_{opt} solution have the same investment cost.

4.6.1 Energy Price

The used energy price in this work is set to be €0.0495/kWh. This is based on the latest full-year accounted for, which is 2015, energy price for industry customers. Between January-June the price was €0.051/kWh and between July-December the price was €0.048/kWh, the used energy price is simply an average over the year. The used consumption category is 2000 - $<$ 20 000 MWh, the energy price includes electricity, grid, electric certificate and taxes (VAT not included) [48].

5
Analysis

5.1 Efficiency Comparison

Within the following sections, positive table-values indicates an efficiency gain for the DC and DC_{opt} solution and are marked with green color. Negative values indicate an efficiency loss compared to the AC case and are marked red.

5.1.1 Distribution Efficiency Comparison

In table 5.1, the distribution efficiency for AC, DC and DC_{opt} are illustrated. The efficiency difference between AC and DC distribution, $\Delta\eta$, results in 1.3%, with advantage DC. As explained in section 4.1.2, based on the physical layout of the distribution system, the efficiency improvement could be higher.

Table 5.1: Distribution efficiency for the AC and the two DC systems.

Load	Efficiency [%]	
	AC	DC & DC_{opt}
Distribution	97.9	99.2

5.1.2 Individual Load Efficiency Comparison

Note that table 5.2 does not take the amount of energy in consideration, just a plain statement of the actual minimum and maximum efficiency difference in comparison to the AC reference case. Table 5.2 is a summary of tables 4.1-4.6, from section 4.4.2. As seen in table 5.2, only the *Lighting* category got improved efficiency for the DC solution over the whole load interval. While two categories, *Lighting* and *Receptacles* are improved over the entire interval for the DC_{opt} solution. The efficiencies in table 5.2 represent the efficiency from grid to end consumption.

Table 5.2: Efficiency interval for DC and DC$_{opt}$ for each individual load.

Load	Type	Efficiency Difference, $\Delta\eta$ [%]	
		Minimum	Maximum
Data Center	DC	-1.1	3.6
	DC$_{opt}$	-0.5	4.3
Lighting	DC	0.3	3.3
	DC$_{opt}$	6.1	9.3
Ventilation Fans	DC	-8.3	7.9
	DC$_{opt}$	-3.2	9.0
Receptacles	DC	-2.5	0.7
	DC$_{opt}$	1.7	5.7
AC Receptacles	DC	-6.6	-3.7
	DC$_{opt}$	-2.6	1.1

5.1.3 Photovoltaic System Efficiency Comparison

Table 5.3 illustrates the efficiency of the photovoltaic installation, consisting of inverter/converter and distribution, as explained in section 4.2.6. The presented efficiency in table 5.3 does not take the load efficiency into account. As seen in table 5.3, the difference in efficiency, $\Delta\eta$, between the DC cases and AC case equals 3.4%. In section 3.5, the total generation is mentioned to be approximately 70 130 kWh/year. If applying the efficiencies from table 5.3, the usable energy on a yearly basis becomes, E_{DC} - E_{AC} = $\Delta E_{PV} \approx$ 2 380kWh/year.

Table 5.3: Photovoltaic installation efficiency for AC and the two DC systems.

Load	Efficiency [%]	
	AC	DC & DC$_{opt}$
Photovoltaic Installation	93.0	96.4

5.2 Savings

Table 5.4 summarizes the energy and financial savings of the DC and DC$_{opt}$ solution. As seen, the benefit of the DC solution is not continuous, whilst the optimized DC solution is. The energy savings in percentage lies within the range of -0.8 to 3.2% for the DC solution and between 4.4 to 8.2% for DC$_{opt}$. Thus, the financial savings in the DC case ranges between €-1 458 to €5 401 and between €8 130 to €13 680 for the DC$_{opt}$ case, per year. Used energy price is as mentioned earlier, €0.0495/kWh, as presented in section 4.6.1.

Table 5.4: Summary of savings with regards to energy in [kWh/year] and [%], together with financial savings in [€/year].

Type	Energy Savings [kWh/year]		Energy Savings [%]		Finance [€/year]	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
DC	-29 450.3	109 119.4	-0.80	3.2	-1 458	5 401
DC_{opt}	164 233.9	276 351.9	4.4	8.2	8 130	13 680

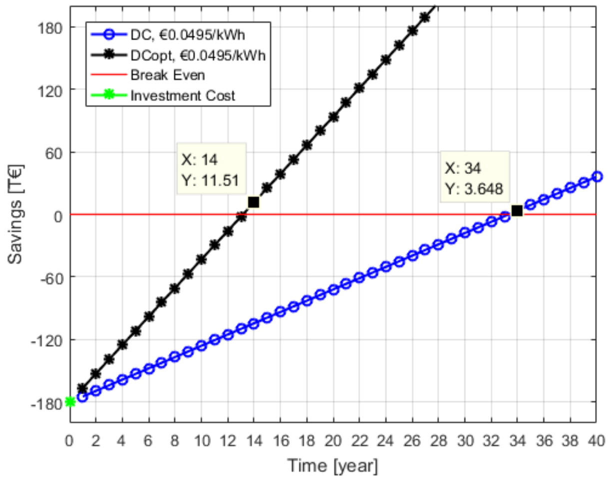
As mention in section 5.1.3, the savings in photovoltaic energy, ΔE_{PV}, is approximately equal to 2 380 kWh/year. With the above mention energy price this results in a yearly saving of approximately €117. Due to the fact that no additional cost arises for a DC solution photovoltaic installation, as mentioned in section 4.6, the saving of €117 is pure profit.

5.3 DC system payback-time

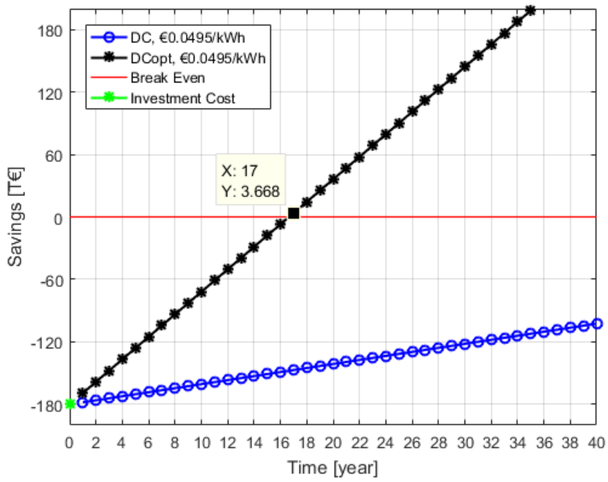
The payback-time for the DC solutions are depending of the energy savings, as seen in table 4.12, from section 4.4.2. Figure 5.1 illustrates the payback-time for three different load distribution scenarios, together with the investment cost and the break-even line. Firstly, figure 5.1a illustrates the most beneficial case which is 50% load at 100% of the time. This load scenario result in a payback-time of 34 years for the DC solution and 14 years for the DC_{opt} solution. Secondly, figure 5.1b illustrates an load case with equal distribution between the three load points, 20%, 50% and 80%. This results in a payback-time of approximate 70 years for the DC solution and 17 years for the DC_{opt} solution. The third and final load distribution is seen in figure 5.1c, this is the least beneficial load distribution, with 80% load at 100% of the time. The result is an infinite payback-time for the DC solution, due to the fact that this solution is less beneficial than the reference AC system and thereby provides no financial benefit. The payback time for the DC_{opt} solution is 23 years. Table 5.5 summarizes the payback-times for the different load distribution cases, i.e. a summary of the information provided in figures 5.1a-5.1c.

Table 5.5: DC solutions payback-time for three different load distributions.

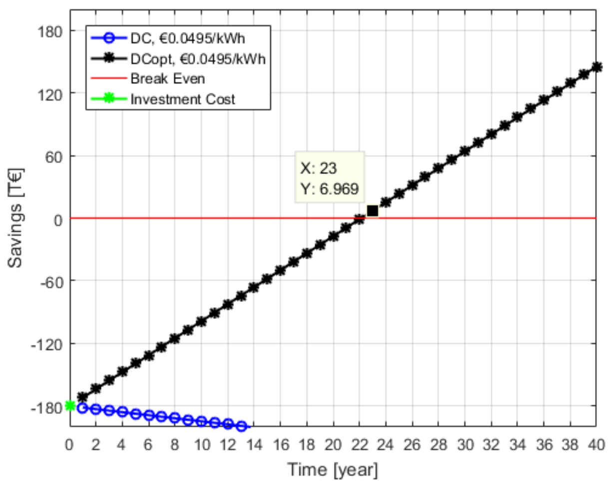
Load Distribution	Type	Payback-time [year]
Best Case (Figure 5.1a)	DC	34
	DC_{opt}	14
Even Case (Figure 5.1b)	DC	70
	DC_{opt}	17
Worst Case (Figure 5.1c)	DC	∞
	DC_{opt}	23



(a) Best case, 50% load, 100% of the time.



(b) Even case, 20%, 50% and 80% load, one third of the time each.



(c) Worst case, 80% load, 100% of the time.

Figure 5.1: Payback-time for three different load case distributions.

6
Conclusion

Two solutions based on DC usage have been evaluated from an efficiency point of view, with constant referencing to a standard AC system. It has been shown that the distribution system benefit from DC usage, where both DC solutions provides an efficiency gain of 1.3%. The same goes for the photovoltaic system installation, which includes the power electronics and distribution, resulting in a 3.4% efficiency gain and an approximate yearly profit of €117. When evaluating the different loads, the results were not unambiguous, a majority of the loads ranged between an efficiency loss and an efficiency gain during the load interval. The only continuously beneficial load for the DC solution were the *Lighting* category, whilst the optimized DC solution showed itself continuously beneficial in *Lighting* and *Receptacles* categories. In overall savings for the DC solution, energy savings ranges between -29 450 kWh/year (-0.8%) to 109 119 kWh/year (3.2%), resulting in yearly financial savings of €-1 458 to €5 401. Overall savings for the DC_{opt} solution, energy savings ranges between 164 234 kWh/year (4.4%) to 276 352 kWh/year (8.2%), resulting in yearly financial savings of €8 130 to €13 680. Loads such as data center, ventilation fans and AC receptacles are shown not to be continuously improved in regards to efficiency, for any of the two DC solution. But, each of these loads, with exception of the AC receptacles, can still be profitable, depending on load distribution.

The investment cost, with previous stated assumptions, is €180 000, resulting in a minimum and maximum payback-time of 34 and ∞ years respectively for the DC solution. Corresponding time for the DC_{opt} solution is minimum 14 years and a maximum of 23 years, for both DC solution an energy price of €0.049/kWh have been used. Based on this, the DC solution is not feasible, due to the fact that the payback-time is longer than the expected life-time of the equipment invested in. Also, the DC solution is not guaranteed to be more efficient than an AC system, which causes insecurity in the investment. The DC_{opt} solution on the other hand, presents a more beneficial solution, where even in worst case, there is still an overall efficiency gain of 4.4% and payback-time of 23 years, which could be considered to be feasible. Thus, to achieve a feasible DC solution for a commercial building such as this, loads must be optimized for DC usage. Meaning unnecessary power electronics, such as rectifiers need to be removed from end consumption units. The rectification should be centralized and strive to achieve as high efficiency as possible.

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