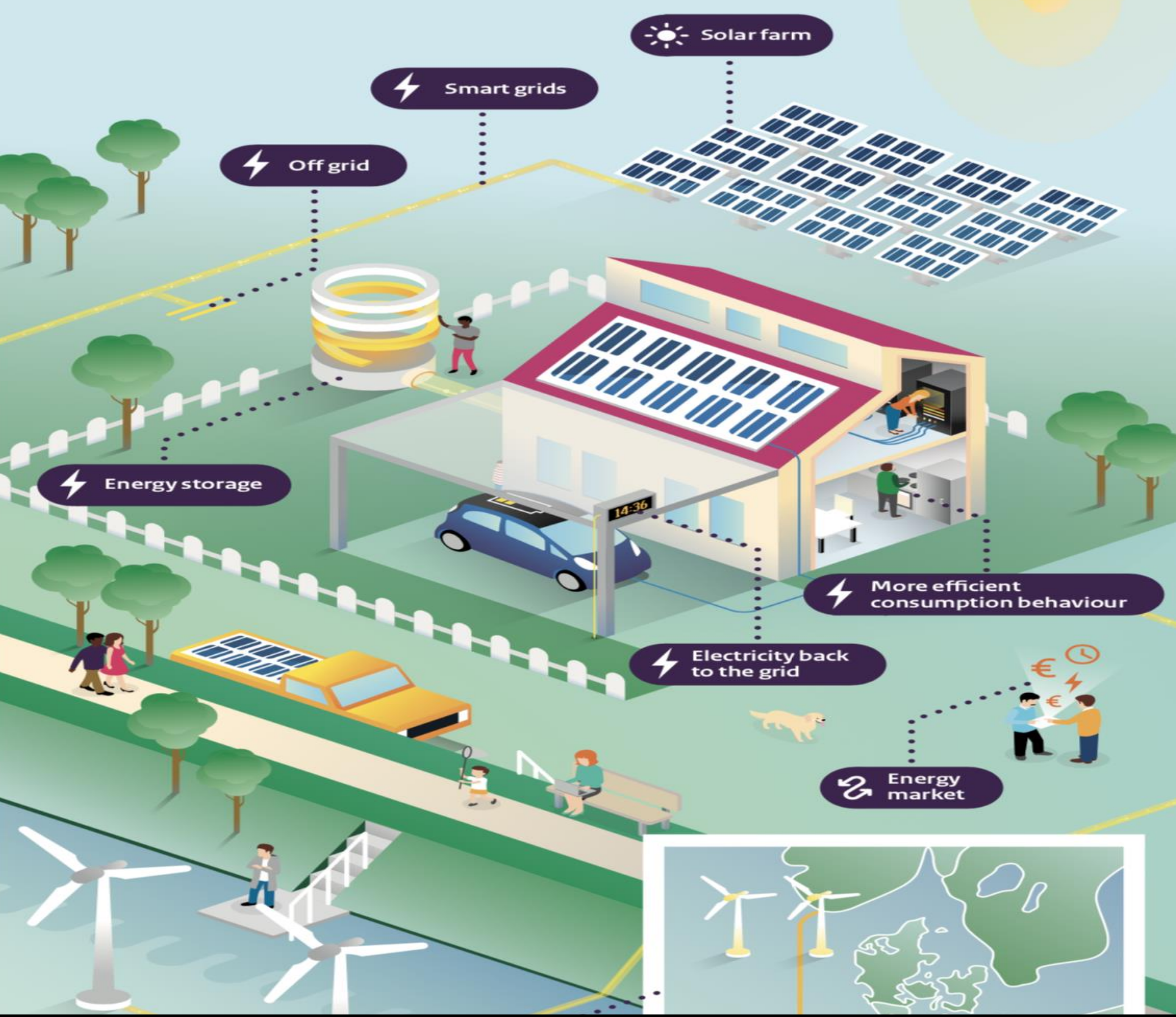

LVDC FOR BUILDINGS IN THE NETHERLANDS

TECHNICAL AND COMMERCIAL POTENTIALS FROM
DC OFFICE LAB

TU Delft

LVDC for buildings in the Netherlands

Technical and commercial potentials from DC Office Lab

by

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in partial fulfilment of the requirements for the degree of

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An electronic version of this thesis is available at http://repository.tudelft.nl/.

TU Delft

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Abstract

Current energy concerns like growing energy demand, the desire for a clean environment and energy conservation started thrusting the society towards distributed renewable electricity generation (DG) technologies. These technologies such as PV solar, Fuel Cells (FC) and urban wind produce Direct Current (DC). The electronic equipment such as laptops, PCs, communication systems, LED lighting, batteries, Electric Vehicles (EV) and Fuel Cell Electric Vehicles (FCEV) also operate in DC. But the present-day electricity distribution system is based on Alternating Current (AC). From this conventional system, the conversion losses can be substantial when DC generation and DC loads are operated. For which, several (DC/AC – AC/DC) conversion steps are required. These conversion losses can be mitigated by removing the intermediate conversion steps and distributing DC power to the DC loads directly. For which, the main aim of the thesis focuses on the technical and commercial potential of Low Voltage DC (LVDC) grids for buildings in the Netherlands.

DC office is a small office building at The Green Village (TGV) in TU Delft where a 350 V_{dc} LVDC system is installed for experimental purposes. The experiments are carried out using both LVDC and LVAC grids in DC Office project. The obtained experimental data are randomized using Matlab to create a year-long load profile. The results are used for discussing the LVDC technical potential in terms of overall efficiency and energy savings. From these results cost-savings are calculated. Along with this, usage of copper and aluminum as electrical conductor in buildings and its investment cost-savings are discussed. For the commercial potential of LVDC grids for buildings in the Netherlands, the Function of Innovation Systems (FIS) approach is used to identify the corresponding LVDC stakeholders, research, pilot projects, rules and regulations and policies for development.

For the technical potential, there are three different cases formulated for analysis. They are ACTube case, DCLED case and ACLED case. In the experiments, tubelights are used in the ACTube case and LEDs are used in the DCLED case, in-order to neglect the energy savings obtained from LED technology, ACLED case is assumed. The overall efficiency of the LVDC grid (DCLED case) is 94.82% and the LVAC grid (ACTube case) is 88.16% and the LVAC grid (ACLED case) is 88.67%. From all these cases, the LVDC grid is around 6.5% more efficient than LVAC grid in small buildings similar to the DC Office. The energy savings obtained by LVDC grid replacing LVAC grid (ACTube) is 2013 kWh/year, and if tubelights in AC are replaced with LEDs in AC, then 1854 kWh/year is estimated to be saved.

The cost-savings are calculated from the energy savings obtained by replacing LVAC grid (ACTube case) with LVDC grid (DCLED case). Considering the total lifetime of the LVDC system as 12 years, the cost savings obtained are € 221.43/year achieving payback in 6 years.

For the commercial potential, using seven functions of FIS it is identified that there are several stakeholders interested in LVDC projects and are responsible for pilot projects. The government also is implementing the new NPR 9090 as the rules and guidelines for LVDC grid installations in buildings. It is also identified that people have positive acceptance of the LVDC grid in their

houses. But the knowledge sharing about LVDC among the society is currently lacking. Moreover, the AC electricity distributors are interested in shifting towards the DC micro grid distribution.

By
Vignesh Subbaraj, Delft,

Nomenclature

A – Ampere
AC – Alternating current
BEV – Battery Electric Vehicles
CaPP – Car as Power Plant
DC – Direct Current
DG – Distributed renewable electricity Generation
EU – European Union
EV – Electric Vehicle
FC – Fuel Cell
FCEV – Fuel Cell Electric Vehicle
FIS – Function of Innovation System
I – Current
LVAC – Low Voltage Alternating Current
LVDC – Low Voltage Direct Current
MLP – Multi Level Perspective
NPR – Dutch Practice Guidelines
P – Power
PV – Photovoltaic
PF – Power Factor
RVO – Rijksdienst voor Ondernemend (Netherlands Enterprise Agency)
SDE – Stimulering Duurzame Energie productie (Renewable Energy subsidy scheme)
SOC – State of Charge
V – Voltage
W – Watt
Wh – Watthour
kWh – kilo Watthour

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Acknowledgement

I dedicate this little thesis to all my teachers at different phases of my life starting from school till my masters at TU Delft.

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Vignesh Bangaru Sakthi Subbaraj
Delft, April 2019

1 INTRODUCTION

The rapid growth of the world's population and their sophisticated living standards by unsustainable methods increase the global warming potential, causing climate change [1]. For mitigating this, the European Union (EU) has set goals for 2020 achieving 20% share of renewables, 20% reduction in CO_2 emissions and 20% improvement in efficiency from 1990 levels. As a result, the Distributed renewable electricity Generation (DG) and green mobility have increased predominantly decreasing the CO_2 emissions.

In continuance from the 2020 goals, the vision of EU 2050 roadmap is to achieve energy savings up to 90% in the buildings sector and 60% in the transportation sector from 1990 levels. One of the main reasons for the EU to focus on buildings and transportation is because these two sectors are responsible for almost 60% of the overall EU energy consumption [2][3]. These goals are common for all the EU-27 countries, of which the Netherlands has also set guidelines for the zero energy buildings by 2050. The electricity demand for buildings is met using the Low Voltage Alternating Current (LVAC) grid for a long time. However, the researchers started to question the efficiency of the current LVAC grid after the increased usage of DG sources. In the current scenario, some of the most common DG technologies are photovoltaic cells (PV), wind energy (on-shore and off-shore) and Fuel Cells (FCs).

DG technologies generate Direct Current (DC) and most of the electronic appliances that we use in our day-to-day life operate in DC. Similarly, in the near future, it is presumed that 50% of our total loads will require DC for operation due to increasing green mobility [2]. This shift towards green mobility will increase the use of Battery Electric Vehicles (BEVs) and Fuel Cells Electric Vehicles (FCEVs) in-turn increasing the DC loads for battery charging.

In the current state of the art, all these DC loads require AC to DC converters when LVAC grids are used in buildings. This is a component which converts the AC voltage to a DC voltage in order to supply DC loads. The utilization of the LVAC grid increases several conversion steps and in-turn increases power conversion losses in the LVAC grid as shown in Figure 1.1. [4]

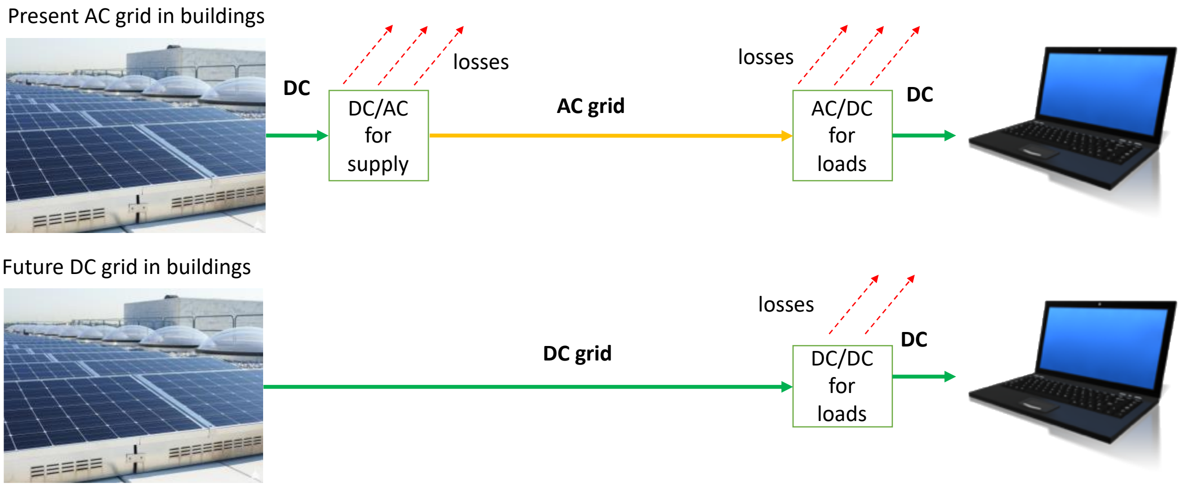


Figure 1.1: Traditional AC distribution with conversion losses and future DC distribution

From the energy savings vision of 2050, the current research focus on reducing the conversion steps and power losses by replacing the LVAC grid with a Low Voltage Direct Current (LVDC) grid in buildings. In the LVDC grid system, the conversion steps are reduced and DC is supplied directly to loads via DC/DC converters. In-order to compare and evaluate LVAC and LVDC grid in a building, a setup has been implemented in a DC office at The Green Village (TGV). DC office is one among many projects that are currently on-going at The Green Village (TGV).

TGV is a test-bed lab facility located at the campus of TU Delft working as a platform for combining new technologies with various innovation partners and society. The ultimate goal of the TGV team is to accelerate development and implementation of innovations. This is achieved by creating a bridge between scientists, engineers, entrepreneurs, public and government for participation, knowledge diffusion and understanding among stakeholders.

The aim of this setup at TGV is to obtain real-time data and analyze the efficiency of LVDC grids in small office buildings. This installed LVDC grid has two systems for testing purpose. One LVDC system is supplied with $48V_{dc}$ and it has PV, a storage battery and DC/DC converters for supply. The DC/DC converters can supply different voltages $60V_{dc}$, $48V_{dc}$, $24V_{dc}$, $19V_{dc}$, $12V_{dc}$ according to the loads. At present, the $48V_{dc}$ lighting is used and later laptops and mobiles can be connected. The DC electricity sources for this system is from PV's generation, battery DC storage and main LVAC utility grid (using a Victron Multiplus bi-converter). The usage of the supply and load strategies are optimized and changeable in Multiplus itself according to the requirements.

In the second LVDC system, the DC voltage is 350 V_{dc} and it has PV and DC/DC converters for loads. The loads used in this system at present are an infrared heater, lighting, laptops and mobile phones. But there is no storage for this system and the DC supply is mainly from PV and from the LVAC grid (using a bidirectional AC/DC current router) as shown in Figure 1.1. The following section 1.1 explains the scope of this thesis using this set up and research questions along with the methodology. Section 1.2 explains the report structure.

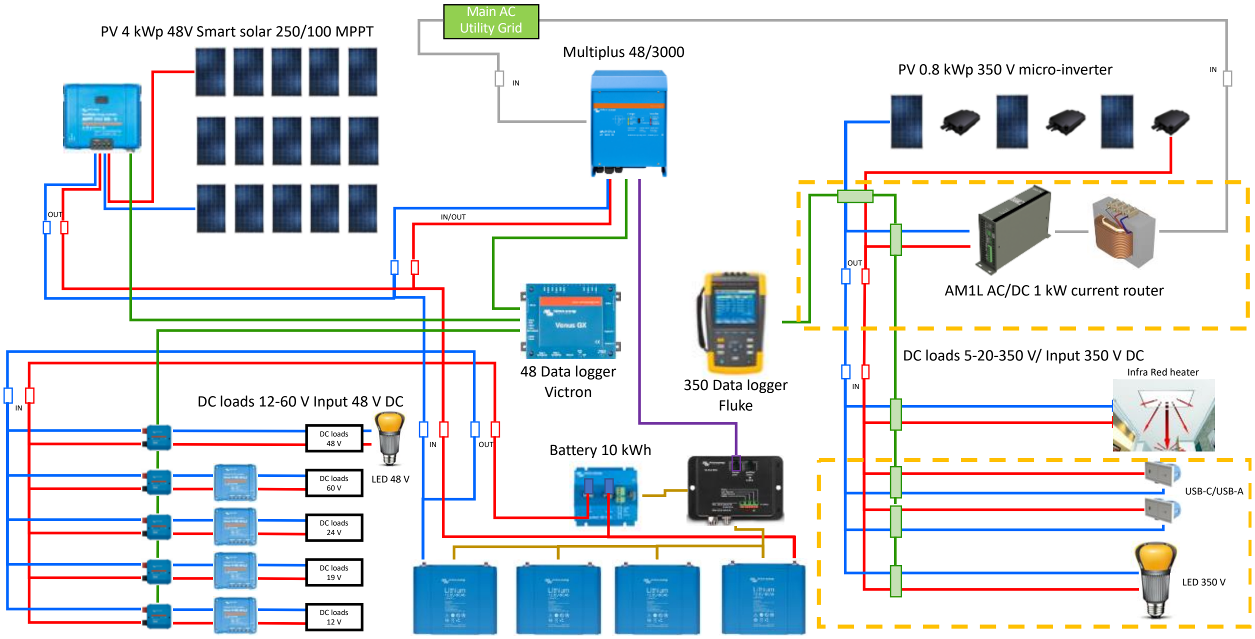


Figure 1.2: Overall Schematics of DC Office setup

1.1 SCOPE OF THESIS

The scope of this thesis is to evaluate the technical efficiency and cost-savings of LVDC grids in small office buildings (similar to DC Office) and to study the commercial potential of LVDC grids in the Netherlands. In-order to achieve the scope, the research focuses to address following questions:

1. *What are the technical efficiency and energy savings of LVDC grid compared with LVAC grid in the DC Office setup?*

The data are measured experimentally from 350V_{DC} LVDC grid and 230V_{AC} LVAC grid that already exists in the DC Office building. The measured data are used to generate a year-long load profile using Matlab. This profile serves as input to evaluate the technical potential of the grids which is further used for the energy savings calculation.

2. *“What are the cost-savings of LVDC grid in DC office setup replacing LVAC grid?”*

The cost savings over a certain period are identified in LVDC and LVAC grids using investment cost and the grid’s energy consumption. Furthermore, the effect of electrical conductor (copper or aluminum) is considered to evaluate the cost savings for both the grids.

3. *"What is the current market scenario of LVDC grids for buildings in the Netherlands?"*

A theoretical framework, Function of Innovation System (FIS) is utilized to identify the stakeholders, installation rules and regulations, incentive policies and acceptance of LVDC grids for buildings in the Netherlands. Figure 1.3 summarizes the overall scope of this thesis.

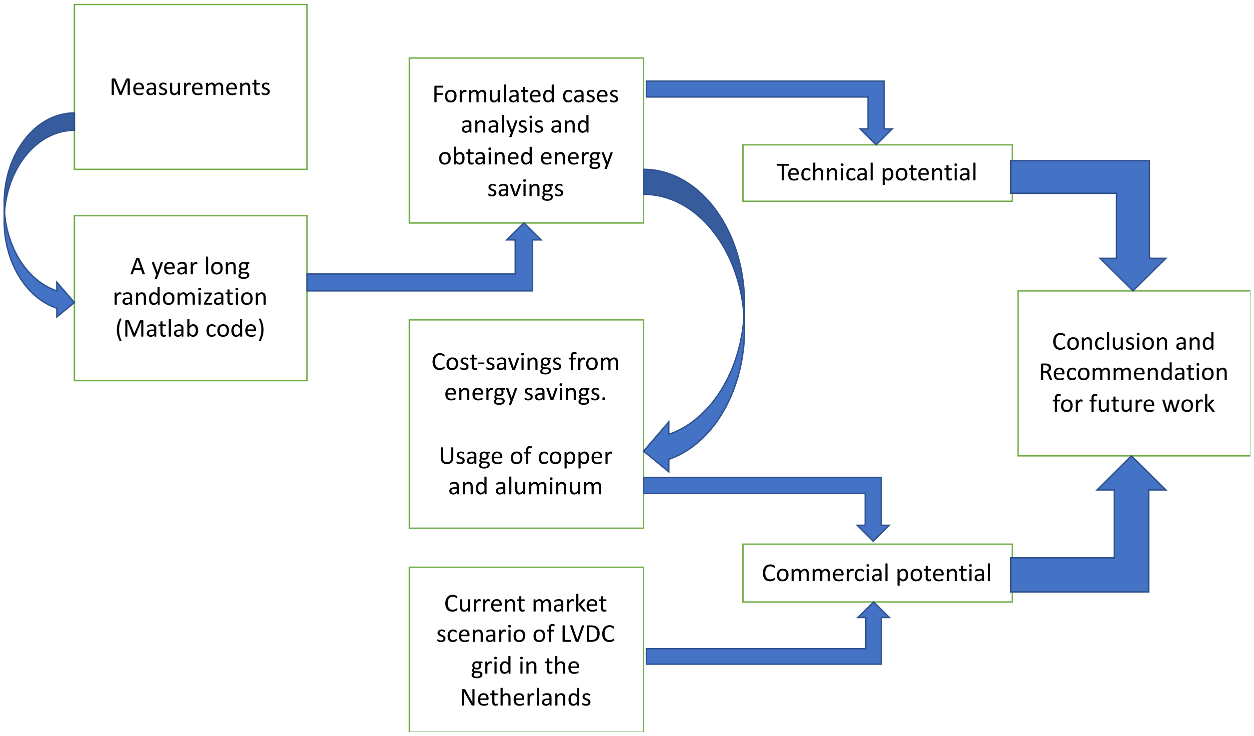


Figure 1.3: Overall scope of thesis

1.2 REPORT STRUCTURE

The content in this document is reported as follows:

Chapter 1 explains the motivation for this thesis, research questions and an overview of existing literature across the globe regarding the same motivation.

Chapter 2 describes a part of DC Office setup used for experiments and describes the measured data from the setup.

Chapter 3 describes randomization methodology used to generate a year-long load profile and the obtained output result for LVDC grid's technical potential.

Chapter 4 discusses the cost savings replacing LVAC grid with LVDC grid from the technical results discussed in chapter 3. Moreover, this chapter also gives a comparison between use of copper and aluminum as a conductor material.

Chapter 5 studies the current scenario of a LVDC grid for buildings in the Netherlands. This is achieved by identifying the current stakeholders, exiting projects, policies and guidelines using seven functions of the FIS.

Chapter 6 gives an overview of the work performed in this thesis and formulate answers to the research questions and gives recommendation for future work.

1.3 LITERATURE OVERVIEW

As stated in section 1.1, the current study focuses on evaluating the technical potential and commercial potential of a LVDC grid in small office buildings. Section 1.3.1 and section 1.3.2 show the literature selected for overview of LVDC grids which is explained further in the following sections.

1.3.1 Literature overview for Technical Potential of LVDC grid in buildings

Daniel et al [5] carried out an experimental analysis to determine and compare the performance of a LVDC grid with a LVAC grid. In this experiment for commercial buildings, Daniel utilized the sensitive DC electronic loads such as computers, coffee makers, fluorescent lamps, etc. These loads were supplied with DC replacing AC supply without modifying the loads. In the LVAC case, the loads were supplied from the main utility LVAC grid and for LVDC case from the AC/DC interface converter as shown in Figure 1.4. It was observed that the use of LVDC supply for sensitive electronic loads have lower losses when compared with a LVAC power supply because of the less conversion steps. The DC voltage for this experiment is selected to be 325 V_{dc} which corresponds to the peak value of the 230V_{rms} AC voltage.

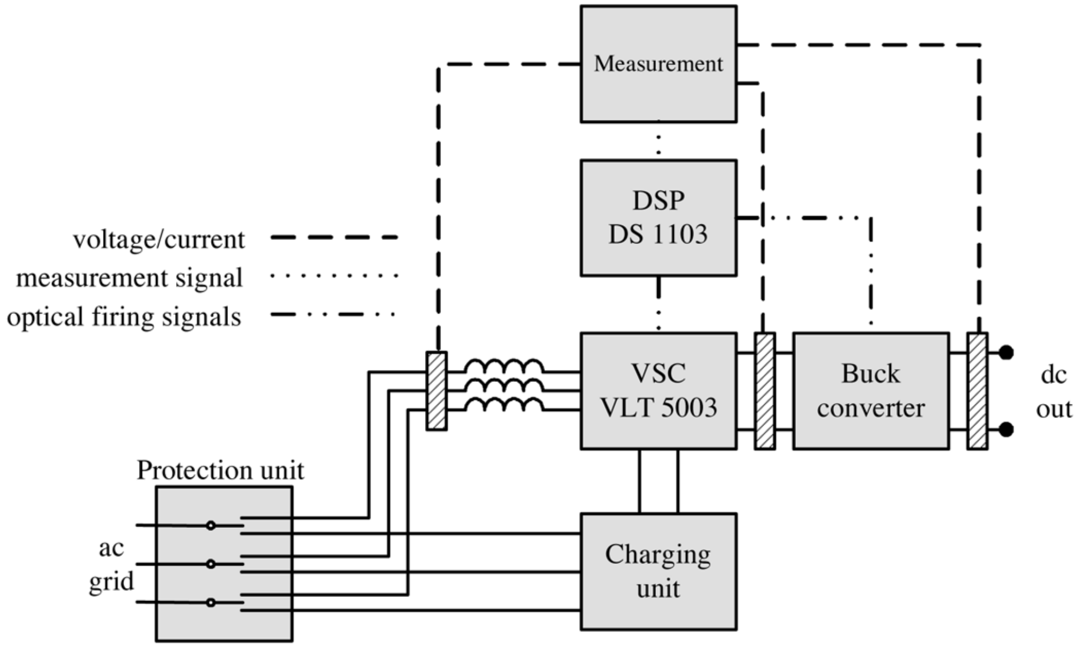


Figure 1.4: Experimental setup of Daniel et al [5].

During the applied transient fault conditions in this setup, the loads experienced voltage fluctuations when operated in AC, but the DC supply from the AC/DC converter maintained a stable voltage for the loads. The authors also tell that the use of a DC grid will add advantages for PV, batteries and Fuel Cells that produce DC, as it can be directly connected or through a DC/DC converter. Since the load can get supply from a DC source, it is possible to remove the rectifiers even inside the loads and losses can be further reduced.

In this setup [5], the energy storage technology is not included, so it was not possible to operate in self-consumption mode. But the authors [5] articulate that if the batteries are combined with this system as energy storage, the voltage variations for the loads can be handled by the battery themselves as long as they range between 85-380V_{dc}.

Similar to this setup, the following literature [6] explains the performance of the 380 V_{dc} LVDC grid setup at Erlangen, Germany. This setup evaluated the performance of a LVDC system consisting of DC lighting, EV charging, a DC micro Combined Heat and Power unit, PV, a grid controller and a LVDC power monitoring unit at Fraunhofer IISB in Erlangen**.** The schematics of the system installed at an office building in Fraunhofer IISB is shown in Figure 1.5.

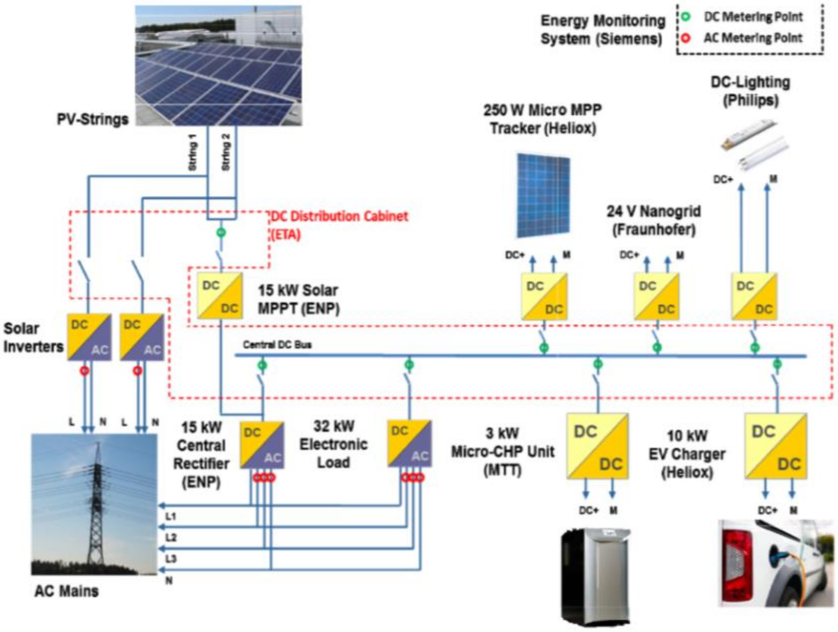


Figure 1.5: Experimental setup of an office building at Fraunhofer IISB in Erlangen [6]

From this experiment, it was observed that the LVDC grid had better operational performance when compared to an LVAC grid. The results plotted in the graph shown in Figure 1.6**,** explain that during the low PV generation and low power demand, the difference in efficiencies for LVAC (92.7%) and LVDC (93.1%) systems is only 0.4%. However, during the high-power demand and high PV generation at 12 P.M, the difference in efficiency for LVAC (86.2%) and LVDC (90.0%) systems increased to 3.8% [6]. In this case, the DC generation is supplied directly to DC loads reducing the usage of AC/DC central rectifier causing the increase in efficiency.

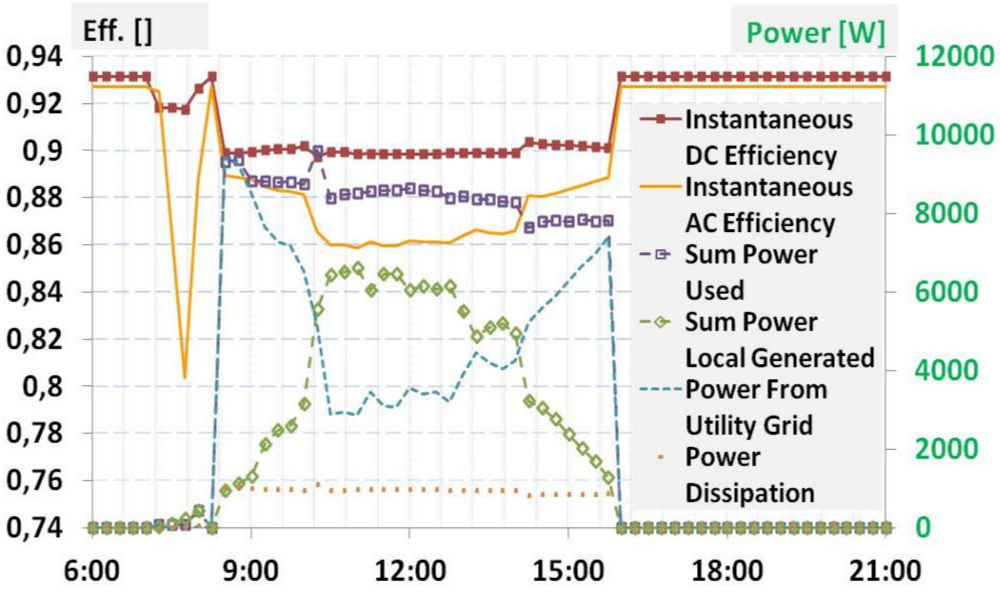


Figure 1.6: Technical efficiencies of the LVDC and LVAC systems [6]

1.3.2 Literature overview for Commercial potential of LVDC grid in buildings

The technical efficiency has to a certain extent been proved through scarce experiments and subsequent analyses. However, the commercial viability is yet to be explored from experimental results. This section discusses the commercial potential of LVDC grid from existing literature related to cost savings and the present market scenario.

Fengyan et al [4] performed a technical and economic analysis of a LVDC grid for commercial buildings for the first time in China using a setup built at Xiamen University. In this setup,

- 150 kWp PV solar,
- 200 Ah 336 V_{dc} lead-acid energy storage unit,
- 160 kW AC/DC unit for standby power supply,
- 30 kW DC air conditioning,
- 40 kW EV charging station and
- 20 kW DC LED lighting system (which uses existing 14 W fluorescent tube lights)

are connected to a 380 V_{dc} microgrid as shown in

Figure 1.7. Fengyan et al [4] also explains that in future, Data centers and various other DC loads will be connected to the LVDC microgrid. Mostly, the rooftop solar and energy storage unit are used for matching the DC loads during peak power generation, whereas the DC air conditioning and the EV charger units are powered from the main utility LVAC grid during low power generation.

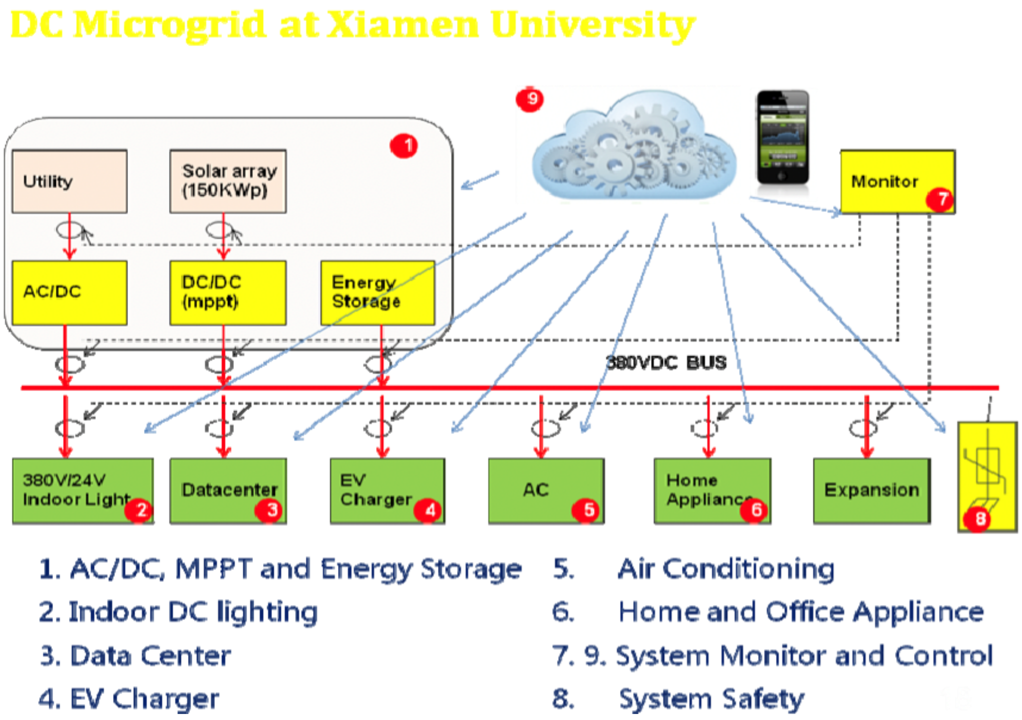


Figure 1.7: Experimental setup at Xiamen university [4].

From this experiment, an economic analysis for this setup was performed as shown in Table 1.1. All these costs include the R&D cost as most of the required technology and products are not yet available in the market. As the products are in the proto stage, the author claims that the costs shown in the table can even be reduced with commercial availability.

Table 1.1: Economic analysis of the setup at Xiamen University [4]

	DC supply setup (US $) (150 kWp)
Total investment	$330K
Incremental cost	$2.2/W
Payback period (no subsidy) @($0.16/kWh)	9 years
Payback period (subsidy $ 0.887/W) @($0.16/kWh)	5.5 years

It was observed that replacing the LVAC grid with a LVDC grid for big commercial buildings will cost $2.2/W with a payback period of 9 years with electricity price of $0.16/kWh. If subsidy of $ 0.887/W is provided, then the investment cost will decrease to $197K for which the payback is achieved in 5.5 years with the same electricity price.

Likewise, TU Eindhoven in collaboration with ABB fixed a LVDC grid setup in the DC Flexhouse project for determining the technical viability of the DC system. Meantime, as a part of DC Flexhouse project, Ploumpidou [2] performed research to assess the market potential of DC applications and challenges in the transition to DC microgrids. For this purpose, the Transition Management framework is utilized to analyze the market scenario of DC grids in the Netherlands.

In the technical analysis of the DC Flexhouse, it was identified that the efficiency of the LVDC architecture increases 2% while using main DC/DC converter and DC bus, whereas along with the DC/DC converters for loads into the DC system increases the overall system efficiency to 5% when compared to the LVAC architecture as shown in Figure 1.8. In Table 1.2, the challenges for transition to DC microgrids were identified and divided into two categories: technical challenges and market challenges using Transition Management framework (TM). This TM formulates the guidelines focusing on strong social actors such as governments, business sectors, scientists, non-governmental organizations and intermediary organizations.

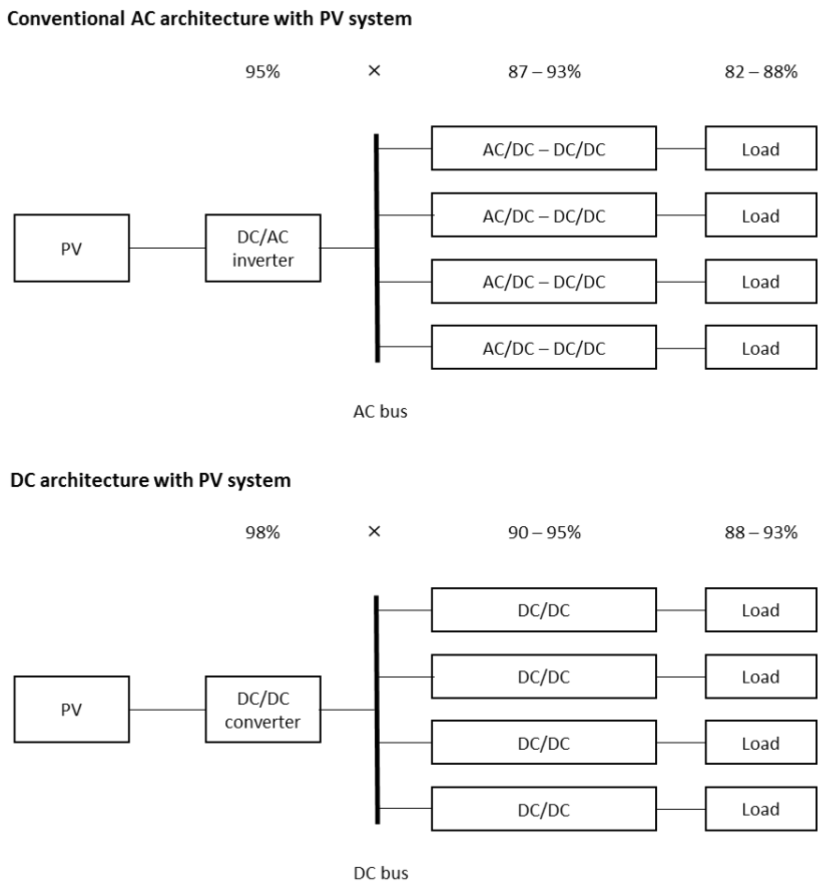


Figure 1.8: Efficiencies of the LVAC and LVDC setup at DC Flexhouse Eindhoven [2]

Table 1.2: Technical and market challenges for the DC transition [2]

Technical Challenges	Market Challenges
Low technology readiness level (still in labs)	Dominating AC technology and its appliances
Nature of DC and different safety requirements in insulation and arch-quenching.	Resistance towards the technological shift from an established regime.
Existing building codes and standards specify AC power and require alteration for DC	Actors are yet to be convinced of the DC potential.
Engineers and technicians need to be trained in handling DC technologies.	Residential energy consumers are not interested in energy-related renovations
Some of the devices need to be re-engineered to work with DC power.	High investment risks
	Technology beginning cost
	Uncertainties in business model innovation
	Unfamiliarity with DC
	Low environmental awareness

From the research [2], it is clear that the LVDC application will initially enter niche markets before penetrating into the mainstream market because the LVDC grid manufacturing and distribution network is very scant when compared to the LVAC grid manufacturing and distribution network. Although the DC encounters technical and market challenges as mentioned in Table 1.2, according to the author [2], increased investments in DC grid technology along with supportive policies will potentially increase the commercial viability of the DC grid system. From the market assessment, DC innovation has a huge potential as it fits within the energy transitions and may well imply a large DC ecosystem. DC can have a huge impact in the niche markets when all the benefits intersects as shown in Figure 1.9.

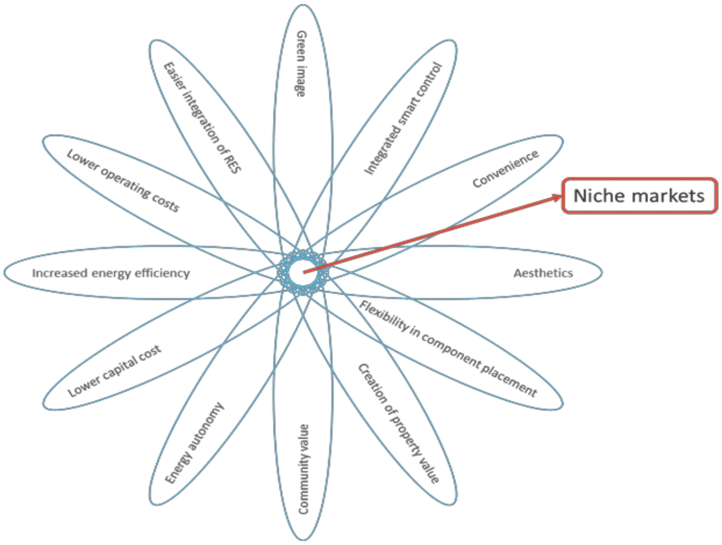


Figure 1.9: Benefits of the DC transition [2]

ABB and other parties that want to promote DC technology should first target to build alliances with co-innovators and find the frontrunners who are willing to invest and adopt the innovation. As DC innovation involves many actors like Grid operators, providers of technology, products and services, energy suppliers, program responsible parties, aggregators and co-innovators; it has to create value for all the actors involved in the DC eco-system in-order to capture the market. But it is a very complicated process as value proposition could differ within the eco-system from actor to actor. This complexity can be solved by amending policies in favor of DC technologies for faster diffusion of the technology [2].

When scrutinizing the literature discussed in sub-section 1.3.1 and sub-section 1.3.2, it can be seen that the LVAC voltage level is 230V_{AC} but for LVDC voltage, there were different levels 325V_{dc}, 350V_{dc}, 360V_{dc}, 380V_{dc} [5][6][4] . This is due to the lack of standardization. For standardization of the LVDC voltage still more experimental results are needed, for which the DC office setup is analyzed for technical and commercial potentials. The following chapter 2 will discuss the 350V_{DC} setup in the DC Office project installed in TGV, TU Delft and its corresponding LVDC and LVAC grids measurement techniques and data gathered.

2 PROJECT SETUP AND MEASURED DATA

This chapter discusses about the measurement techniques, measurement devices, measured parameters and data obtained from LVDC and LVAC grids in DC Office project setup. Section 2.1 explains the DC Office setup used for experiments. Section 2.2 discusses about the methodology, parameters measured and also the parameters selected for comparison. Section 2.3 explains the measured data for the loads.

2.1 DC OFFICE PROJECT SETUP considered for this thesis

In the area of 250 m^2 DC office shown in Figure 2.1, there are various real-time loads for daily usage such as tubelights, laptops, mobile phones, monitors, projectors, data center, dishwasher and the heat pump. The aim is to compare the overall efficiency of the LVDC grids with the LVAC grids in a building. In-order to measure the overall performance of these real time loads in LVDC grid separate cabling and wiring setup were provided with DC input and measurement points. For the overall performance measurement in LVAC grids, the existing LVAC grid of the office was used. Among the different loads, only a few are selected due to nature of the experiment. All the loads that are used in AC are also characterized in DC with exception of tubelights in AC and LEDs in DC. The loads that are considered for this experiment are given in Table 2.1.

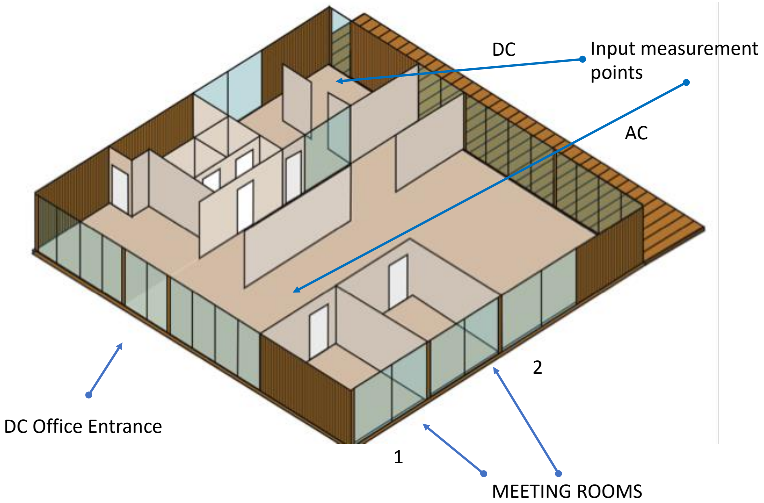


Figure 2.1: DC Office infrastructure

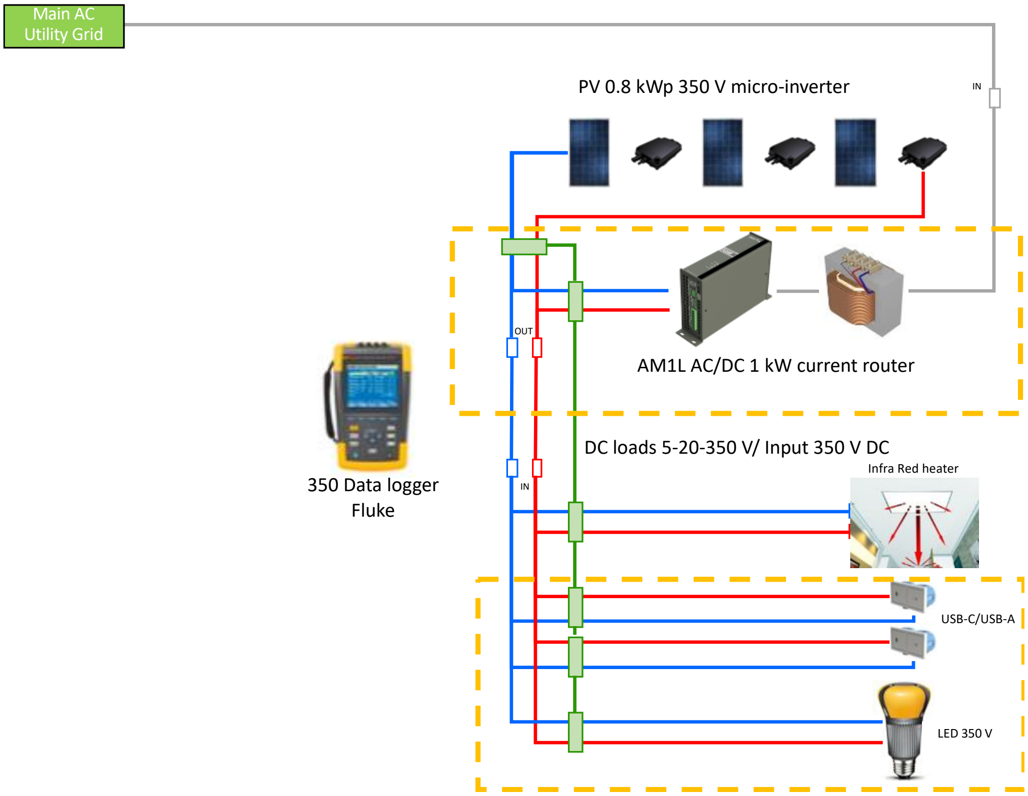


Figure 2.2: 350Vdc setup considered for this experiment (dotted yellow line – except infrared heater)

Table 2.1: Components used as loads in this experiment

AC Loads – 230V_{ac}	**DC Loads – 350V_{dc}**
Tubelight	DC LED
Laptop 1 – MacBook Pro – 15 inches (USB C)	Laptop 1 – MacBook Pro – 15 inches (USB C)
Laptop 2 – MacBook Pro – 13 inches (USB C)	Laptop 2 – MacBook Pro – 13 inches (USB C)
Mobile Phone – iPhone – SE	Mobile Phone – iPhone – SE

DC/DC converter for laptops and mobile

AC/DC converters for Mobiles (top) and Laptops (bottom)

Figure 2.3: Converters used for this experiment (2-AC/DC converters for 2-laptops, 1-AC/DC converter for mobile phone)(1-DC/DC converter for all 2-laptops and 1 mobile phone)[7][8]

Since the electronic components inside the laptops, mobile phones and LED drivers functions only in DC, the manufacturers provide bulky AC/DC adapters/converters along with the devices as shown in Figure 2.3 (left) to operate these loads in AC supply. These converters are used to convert 230V_{ac} to operating output DC load voltages. Also, for DC supply, the DC/DC converters as shown in Figure 2.3 (right) are used to convert 350V_{dc} into corresponding operating output DC load voltages. These DC/DC converters are prototypes designed for max 100 Wdc output (Output: 20V_{dc}; 5A_{dc}) from a company named 'Direct Current B.V'[8] whereas for laptop 1 the AC/DC converter is 87$W_{dc, out}$ and for laptop 2 it is 61$W_{dc, out}$ by Apple [7]. Table 2.2 and Table 2.3 shown below are the input and output specifications of the loads used in AC and DC.

Table 2.2: Electrical specifications for AC loads

AC loads	**AC Input Parameters for converters**		**Operational DC Output Parameters for components (Except tubelights)**	
	Voltage (V_{in}) V_{ac}	Current (I_{in}) A_{ac}	Voltage (V_{out}) V_{dc}	Current (I_{out}) A_{dc}
Laptop1 (87 W) (AC/DC converter)	(100 -240)	1.5	20.2	4.3
Laptop2 (61 W) (AC/DC converter)	(100 -240)	1.5	20.3	3
iPhone – SE (5W) (AC/DC converter)	(100 -240)	0.15	5	1
Tubelight (along with ballast)	240	0.21	-	-

Table 2.3: Electrical specification for loads in DC

DC loads	**DC Input Parameters for converters**		**Operational DC Output Parameters for components**	
	Voltage (V_{in}) V_{dc}	Current (I_{in}) A_{dc}	Voltage (V_{out}) V_{dc}	Current (I_{out}) A_{dc}
Laptop1 (87W) (DC/DC converter)	(350 – 380)	0.28	20	5
Laptop2 (61 W) (DC/DC converter)	(350 – 380)	0.28	20	5
iPhone – SE (5 W) (DC/DC converter)	(350 – 380)	0.0214	5	1.5
Philips – LED (with driver)	(350 – 380)	0.12	-	-

For LVDC experiments, a new setup with new wires and connecting sockets are fixed in pillars as shown in Figure 2.4. The LVAC and LVDC grids in the DC Office setup function independently. The parameters required for analysis will be discussed in section 2.2.

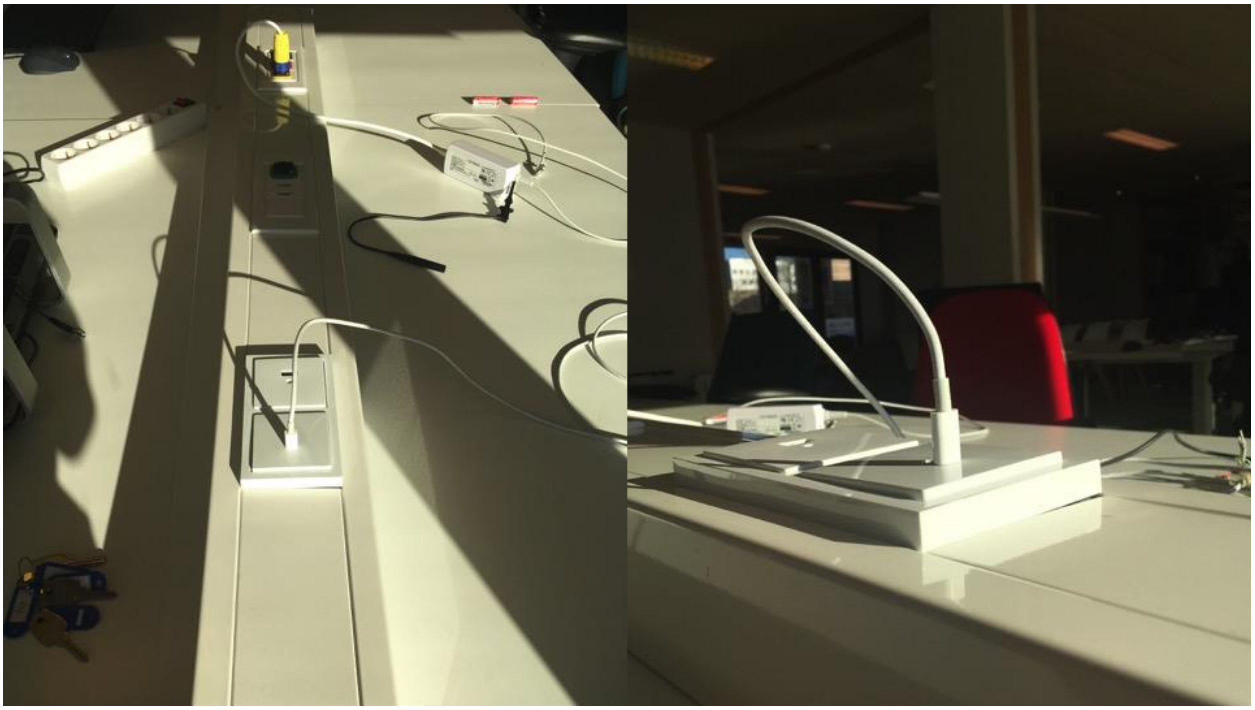


Figure 2.4: Connection sockets in pillar for laptops and mobile phones (LVDC experiment)

2.2 Parameters for LVAC and LVDC comparison:

The Table 2.4 shows the parameters that are measured for the comparison of the LVAC and LVDC grids. In-order to compare, only common parameters are selected for calculations explained in section 2.2.1. The description of each compared parameter is given below.

Table 2.4: Electrical Parameters measured for DC and AC loads

Components	**LVAC**		**LVDC**	
	Input (all AC)	**Output (all DC)**	**Input (350V$_{dc}$)**	**Output**
Laptop 1	• Voltage ($V_{ac,\ rms\ in}$) • Current ($A_{ac,\ rms\ in}$) • Active Power ($W_{ac,in}$) • Apparent power (VA) • Reactive power (VAR) • Power factor • Active Energy (kWh) • Apparent Energy (VAh) • Reactive energy (VARh)	• Voltage dc ($V_{dc,out}$), • Current dc ($A_{dc,out}$) • Active Power ($W_{dc,out}$)	• Voltage dc ($V_{dc,in}$), • Current dc ($A_{dc,in}$) • Active Power dc ($W_{dc,in}$)	• Voltage dc ($V_{dc,out}$), • Current dc ($A_{dc,out}$) • Active Power dc ($W_{dc,out}$)
Laptop 2				
iPhone – SE				
Tubelight		-	N/A	N/A
Philips-LED	N/A	N/A	• Voltage dc (V_{dc}), • Current dc (A_{dc}) • Power dc (W_{dc})	-

1) Voltage (V) and Current (I) – The voltage is the potential difference between the two points which drives the electrons from one point to another. This flow of electrons is known as current. Voltage and Current in AC are sinusoidal wave with 50 Hz frequency. But DC has a constant voltage over time as shown in Figure 2.5.

The devices that are designed to operate at a rated 230 $V_{ac,\ (RMS)}$ have AC peak voltage of 325 V. Including ±5% tolerance [9], the peak value of V_{ac} is calculated as:

$$\mathrm{V}_{\mathrm{ac,\ peak}} = \sqrt{2} * 1.05 * 230 \approx 341\ \mathrm{V}$$

Due the lack of standardization of DC voltage in the market, the most common values of LVDC 380Vdc, 360Vdc, 350Vdc are used and experimented for standardization around the world [5][6][4]. As we have the peak value of 341 Vac in LVAC grid, the closest DC value of 350Vdc setup is chosen for the new LVDC 'DC Office' experimental setup.

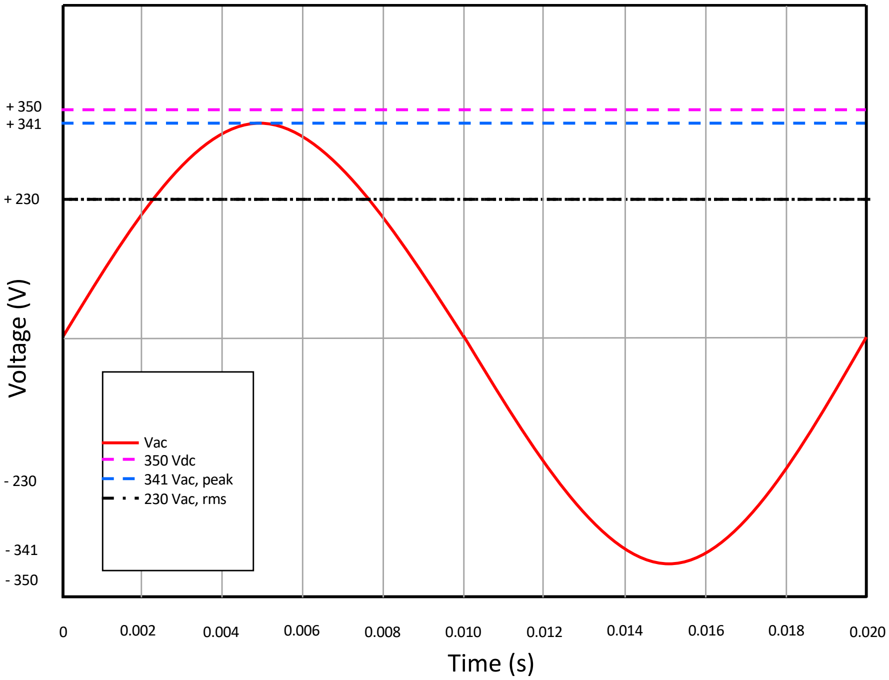


Figure 2.5: Nature of AC and DC electricity

2) Power (P) –The AC and DC powers are compared as shown in Table 2.5.

Table 2.5: Types of powers in AC and DC

Powers	
AC	**DC**
Active Power P (W)	Active Power P (W)
Apparent Power S (VA)	
Reactive Power Q (VAR)	

In DC, the product of DC voltage and DC current is the active power (P), whereas in AC the product of AC voltage and AC current is the apparent power (S). This is because of the reactance present in AC circuit. For comparison of LVAC and LVDC grids, the power's compared should be the same. In-order to get the active power (P) in AC, the phase angle between active power and the apparent power known as power factor or CosΦ is required. The product of AC voltage, AC current and phase angle gives the active power (P) in AC.

- Active power P (W) – The active power is a useful amount of power utilized in AC or DC circuit to do work. The formula for active power in AC, (P_{ac}) = $V_{ac,rms}$*$I_{ac,rms}$* CosΦ and in DC, P_{dc}= V_{dc}*I_{dc}. The unit of active power P is watts (W).

- Reactive Power Q (VAR) – The reactive power is an imaginary power as it does not contribute to do work. This power exists only in AC circuits when used by reactive loads such as inductors, transformer and capacitors. In principle, these loads cause phase shifting for the voltage ($V_{ac,rms}$) and current ($I_{ac,rms}$) due to AC's alternating nature (50 Hz frequency). The formula for reactive power is Q = $V_{ac,rms}$*$I_{ac,rms}$* SinΦ and its unit is expressed as VAR.

- Apparent Power S (VA) – In terms of active power (P) and reactive power (Q), the apparent power S is represented as $\sqrt{(\text{active power})^2 + (\text{reactive power})^2}$. The total power in an AC circuit is apparent power (S).

- Power Factor (PF) or CosΦ – The power triangle in Figure 2.6 gives a relation between active power, reactive power and apparent power. The ratio of active power and the apparent power is known as the power factor.

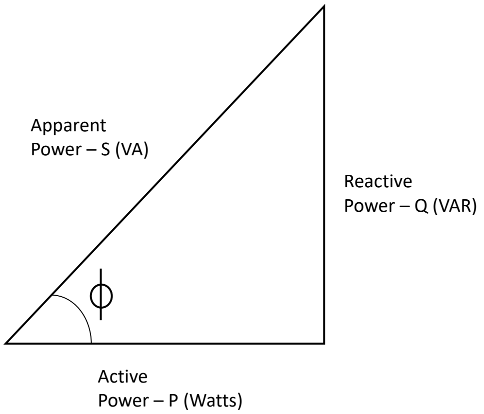


Figure 2.6: Power triangle

3) Energy – Energy is known as the amount of power consumed with respect to the time. For example, if 10 W of active power is consumed for 1 hour, then the active energy consumed will be 10W*1hour = 10Wh. The unit of active energy is Wh.

From the parameters discussed above, only the active energy consumed per year (Wh/year) is applied to express the overall efficiency, energy savings and losses in LVAC and LVDC grids. This will be discussed in the following section.

2.2.1 Overall efficiency, energy savings and losses

The input active power denoted in Table 2.4 is measured along with conversion losses and line losses. For identify overall efficiency of LVDC grid and LVAC grid, these losses should be considered. These losses are calculated as follows.

From the input and output parameters measured, the efficiency of the converters utilized in LVAC and LVDC grids will be identified. The formula for the efficiency of the converters are [10]:

$$Converter\ efficiency\ (AC) = \frac{Pdc, out}{Pac, in} * 100$$

$$Converter\ efficiency\ (DC) = \frac{Pdc, out}{Pdc, in} * 100$$

Equation 1: AC/DC converter and DC/DC converter efficiencies

The line power losses are calculated from the current measured and resistance (R) of conducting material using the formula:

$$Line\ power\ loss\ (both\ AC\ and\ DC) = \mathrm{I^2R\ (W)}$$

Equation 2: Line loss for LVAC and LVDC

To calculate the conversion power loss, the measured input active power, calculated converter efficiencies and line power loss are used. This is expressed in the equation below:

$$Conversion\ power\ loss\ (both\ AC\ and\ DC) = \text{(Active power measured – Line power loss calculated) – (1 – converter efficiency)}$$

Equation 3: Conversion power loss for LVAC and LVDC

These loss calculations are performed for all the loads and the corresponding energy losses are calculated. All the parameters measured and calculated are arranged in an input excel file for generation of a year-long load profile using Matlab code (see chapter 3). From the final results of Matlab, the overall efficiency of the LVAC and LVDC grids are calculated using the formula below:

$$Overall\ efficiency\ of\ grid = 100 * \left(1 - \frac{Energy\ losses\ (kWh/year)}{Active\ energy\ for\ load\ (kWh/year)}\right)$$

Equation 4: Overall efficiency of LVAC and LVDC grids

2.3 Measurement technique

During the initial phase measurements, investigation was done by operating the office setup in DC for 1 month. After performing number of trials using the DC setups, various technical comparison difficulties and uncertainties in manual measurements were encountered (discussed in Appendix A). From these trials, a modified measurement technique is proposed and executed as discussed in this section. The FLUKE measurement devices for metering LVAC and LVDC parameters in building are shown in Table 2.6. From the specification sheet of the devices, it is identified that these FLUKE devices have an accuracy of ±0.5% for the parameters considered in Table 2.4. [11]

Table 2.6: Measurement devices used in the experiments

Components	Measurement Devices for Input parameters		Measurement Devices for Output Parameters	
	LVAC	LVDC	LVAC	LVDC
Laptop 1 and Laptop 2	FLUKE Scopemeter (For both input and output)			
iPhone – SE	FLUKE 435 Series II Power loggers		1. FLUKE 289 true RMS multimeter – For current. 2. Normal Multimeter – For Voltage	
Tubelights	FLUKE 435 Series II Power loggers		-	-
Philips – LED	FLUKE 435 Series II Power loggers		-	-

From the several iterations of measurements, for the laptops and mobile phones, it is observed that the efficiencies of the AC/DC and DC/DC converters vary when the laptop is at 0% SOC (State of Charge) (max load) and 100% SOC (State of Charge) (min load) (discussed in Appendix A). The efficiencies of these converters rely on both the input and output parameters. So, a FLUKE scopemeter is used for measurements where both input and output parameters can be measured in a single device. This technique is used in-order to avoid manual recording errors. For mobile phones, the scopemeters are not used due to the scopemeter setup limitations and time constraints (appendix A). So, for mobile phones the output parameters are measured manually using two multimeters from which the efficiencies are calculated.

Due to setup limitations for lighting loads such as tubelights in LVAC and LEDs in LVDC, only the input parameters mentioned were measured using device given in Table 2.6. It is estimated that the efficiencies are almost constant for lighting loads due to the constant power drawn from the grid. The efficiency estimation of lighting loads is discussed in section 2.4.

During measurements, the loads were measured individually. For instance, when tubelights are turned on, other loads are not connected. When a mobile phone is connected the other loads are turned off and so on. When all the loads are connected at once the results obtained are the almost same as the sum of individually obtained results.

2.3.1 LVAC measurement technique:

For LVAC measurements, one power logger is fixed in the entrance of Meeting room 1 (Ref Figure 2.1) as shown in Figure 2.7. The AC supply is drawn from the main AC grid and the loads used for measurement are tubelights (4 – No's), laptop 1 (DC load), laptop 2 and a mobile phone (DC load). These devices were shut down and only the internal battery is considered as the load. The laptops and mobile phones are charged from 0 – 100% SOC. The four tubelights in the meeting room 1 are connected with one switch. So, the measurements are logged for 4 tubelights. The recorded data for tubelights and other loads is sampled and stored at 1-minute time intervals during office working hours from 8:00 AM to 6:00 PM.

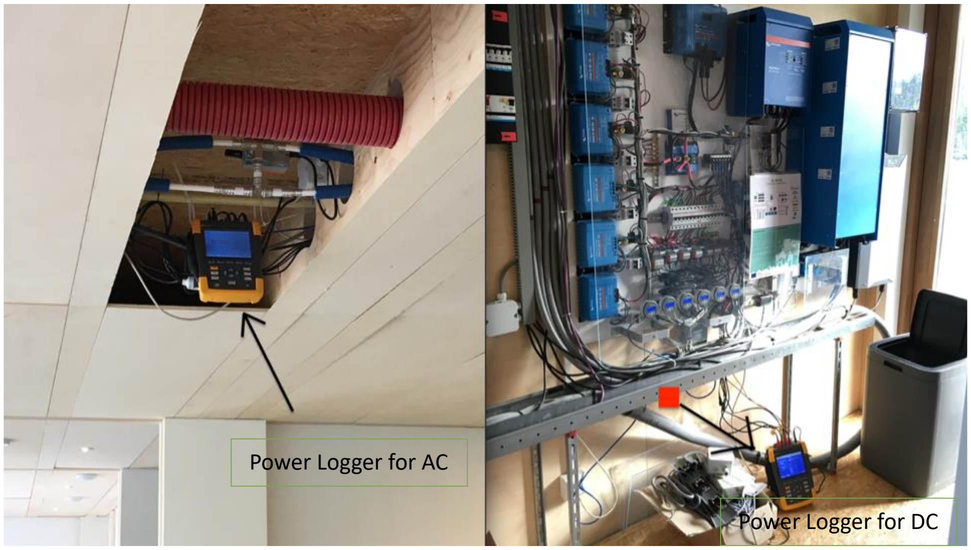


Figure 2.7: Installation of Input power logger for AC (left – in-front of meeting room 1) and input power logger DC (Right – installation room)

2.3.2 LVDC measurement technique:

For LVDC measurements, the other power logger is fixed in the installation room as shown in Figure 2.7. The DC loads used for measurements are DC LEDs (2), laptop 1, laptop2 and a mobile phone. The DC supply for these loads are drawn from the AC/DC current router which supplies 350 V_{dc} into the LVDC grid setup (reference Figure 2.2). The rest of the procedure followed in LVDC measurements are same as LVAC measurements, this is followed in order to maintain the reliability of the data. The only difference in the AC and DC setups is that tubelights are used for lighting in AC whereas LEDs are used for lighting in DC. The average illumination or brightness and efficiency of 2 LEDs is greater than 4 tubelights, so 2 LEDs are used to replace 4 tubelights.

2.4 INPUT DATA GATHERED FROM MEASUREMENTS

The parameters are measured for 10 hours and recorded at 1-minute intervals which makes total 600 minutes of data from 8:00 AM till 6:00 PM for each device. For conciseness, only few random data from the measured file are shown for all the loads.

From Table 2.7 and Table 2.8, it can be seen that active power measured for tubelights and LEDs are constant throughout the operation. For the light loads in LVAC, there is an electronic ballast used for starting the tubelight, which has constant efficiency of 89.9% [12]. Similarly, at maximum constant load the efficiency of the DC LED driver is 96% [13].

Table 2.7: Parameters measured for 4 tubelights using Power logger

Time	Voltage $V_{ac,\ in}$	Current $A_{ac,\ in}$	CosΦ	Active Power $W_{ac,in}$	Active Energy $Wh_{ac,in}$/min	Ballast efficiency
8:00	228.89	0.819	0.9	169.8	3	89.9%
12:00	228.23	0.810	0.9	168.3	2	
16:00	229.87	0.826	0.9	169.6	3	
18:00	229.49	0.820	0.9	169.4	3	

Table 2.8: Parameters measured for 2LEDs using Power logger

Time	Voltage $V_{dc,\ in}$	Current $A_{dc,\ in}$	Active Power $W_{dc,in}$	Active Energy $Wh_{dc,in}$/min	DC LED driver efficiency
8:00	349.70	0.245	85.677	1.428	96%
12:00	349.82	0.247	86.405	1.440	
16:00	349.86	0.248	86.765	1.446	
18:00	349.86	0.247	86.415	1.440	

Laptop 1, Laptop 2, and the mobile phone (iPhone) loads are discussed as follows. These loads are not a constant load, the parameters measured are for one full cycle of charge from 0 – 100 % SOC of the battery. At 0% SOC, the load is maximum and when the SOC is close to 100% the load is minimum. According to the SOC, the efficiency for both converters are calculated as discussed in section 2.2.1 and shown in Table 2.9 and
Table 2.10 for Laptop 1 and Table 2.11 and Table 2.12 for Laptop 2.

In AC measurements Table 2.9 and Table 2.11, for Laptop 1 (MacBook Pro (15”) – USB C, 87 W) and Laptop 2 (MacBook Pro (13”) – USB C, 61 W), the efficiency pattern of the AC/DC converters from 0 – 100% of SOC is almost similar. This is because the AC/DC converters provided by the manufacturers are well designed for the specific model. Likewise, comparing the DC measurements from
Table 2.10 and Table 2.12, Laptops 2 have efficiencies slightly low than laptop 1 for their corresponding SOC’s. This is due to the fact that the prototype DC/DC converter used in this experiment is designed for max power capacity of 100 W which is higher than the power capacity of both the laptops [9]. Nevertheless, the DC/DC converter have high efficiencies compared to the AC/DC converters at maximum loads (0% SOC), it should be noted that in minimum load (100% SOC), both AC/DC and DC/DC converters have almost same efficiencies which is shown in Figure 2.8, discussed similar in literature [9].

Table 2.9: Parameters measured for Laptop 1 in AC using scopemeter and AC/DC converter

Battery SOC (%)	**Input Parameters**		**Output Parameters**		**Efficiency**
	Current $A_{ac, in}$	Power $W_{ac, in}$	Current $A_{dc, out}$	Power $W_{dc, out}$	$(W_{dc,out}/W_{ac,in})*100$
0	0.376	79	3.530	70.694	89.5%
25	0.384	80	3.580	71.606	89.5%
50	0.370	77.44	3.452	69.044	89.2%
75	0.335	39	1.720	34.5	88.5%
100	0.154	16	0.677	13.550	84.6%

Table 2.10: Parameters measured for Laptop 1 in DC using scopemeter and DC/DC converter

Battery SOC (%)	**Input Parameters**		**Output Parameters**		**Efficiency**
	Current $A_{dc, in}$	Power $W_{dc, in}$	Current $A_{dc, out}$	Power $W_{dc, out}$	$(W_{dc,out}/W_{dc,in})*100$
0	0.220	77.428	3.620	71.937	93%
25	0.246	86.541	4.064	80.607	93%
50	0.189	66.627	3.100	61.762	92.6%
75	0.110	38.654	1.710	34.296	88.7%
100	0.053	18.827	0.814	16.394	87%

Table 2.11: Parameters measured for Laptop 2 in AC using scopemeter and AC/DC converter

Battery SOC (%)	**Input Parameters**		**Output Parameters**		**Efficiency** $(W_{dc,out}/W_{ac,in})*100$
	Current $A_{ac,\ in}$	Power $W_{ac,\ in}$	Current $A_{dc,\ out}$	Power $W_{dc,\ out}$	
0	0.430	50.056	2.241	44.883	89%
25	0.363	41.5	1.859	37.183	89%
50	0.289	33	1.470	29.4	89%
75	0.220	23.778	1.054	21.033	88%
100	0.154	16.056	0.683	13.556	84%

Table 2.12: Parameters measured for Laptop 2 in DC using scopemeter and DC/DC converter

Battery SOC (%)	**Input Parameters**		**Output Parameters**		**Efficiency** $(W_{dc,out}/W_{dc,in})*100$
	Current $A_{dc,\ in}$	Power $W_{dc,\ in}$	Current $A_{dc,\ out}$	Power $W_{dc,\ out}$	
0	0.162	57.101	2.643	52.767	92%
25	0.155	54.501	2.501	49.951	92%
50	0.117	41.301	1.839	36.866	89%
75	0.084	29.724	1.281	25.730	87%
100	0.046	16.220	0.680	13.7	84%

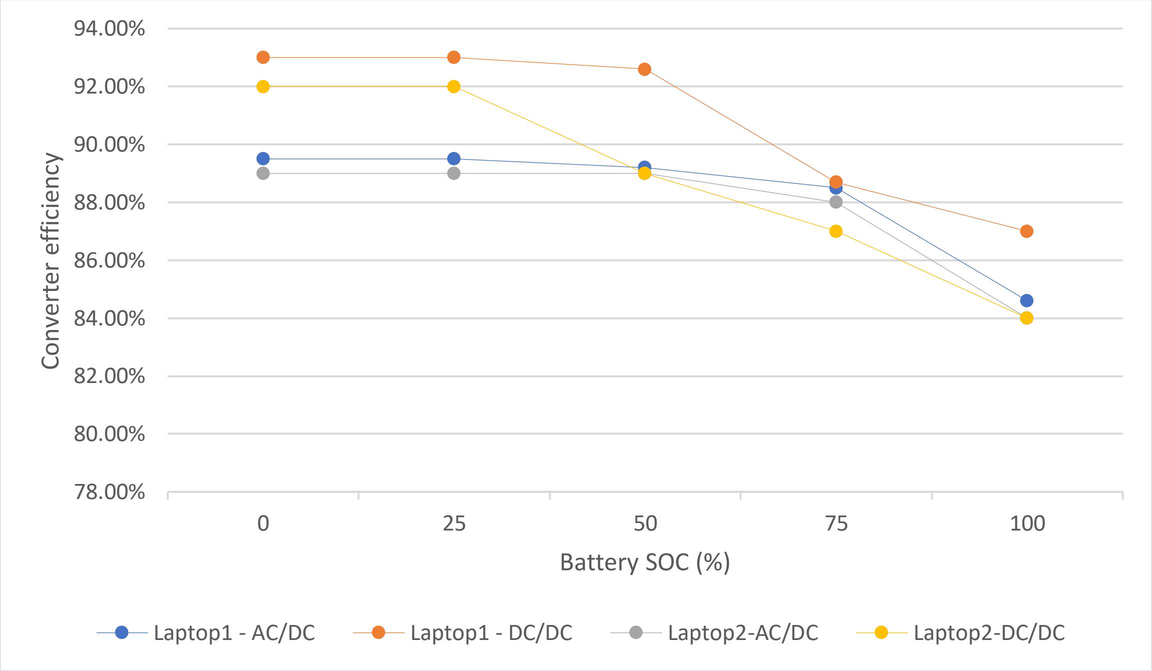


Figure 2.8: Battery SOC vs efficiency of AC/DC and DC/DC converters for laptops operating in LVAC and LVDC grids

On the other hand, for mobiles phones, the efficiencies of AC/DC converter are higher than the DC/DC converter. This is because AC/DC converter provided by the manufactures is well established in the market whereas the DC/DC converter used for this experimental purpose is a prototype. Moreover, the output parameters measured for mobiles phone were performed manually. The Table 2.13 and

Table 2.14 show the input and output parameters for mobile phone in AC and DC setup using instruments shown in Table 2.6. When the current in Table 2.13 and

Table 2.14 are compared with each other, the DC has low current because of the higher voltage (350 V_{dc}) and no reactive current. But the AC current has a reactive current included in it ($V_{ac}*I_{ac}$ = Apparent power) as discussed in section 2.2.

Table 2.13: Parameters measured for mobile phone in AC using power logger and AC/DC converter

Battery SOC (%)	Input parameters recorded in power logger				Output parameters measured using multimeters			
	Voltage $V_{ac, in}$	Current $A_{ac, in}$	CosΦ	Active power in (W_{ac})	Voltage out ($V_{dc, out}$)	Current out ($I_{dc, out}$)	Power out ($W_{dc,out}$)	Adapter Efficiency ($W_{dc,out}/W_{ac,in}$)*100
0	235.82	0.06	0.48	6.8	4.9	0.916	4.49	66%
25	235.75	0.061	0.48	6.9	4.9	0.936	4.59	66%
50	232.66	0.062	0.48	6.9	4.9	0.941	4.61	67%
75	235.05	0.048	0.46	5.2	5	0.668	3.34	64%
100	235.42	0.028	0.37	2.5	5.1	0.249	1.27	52%

Table 2.14: Parameters measured for mobile phone in DC using power logger and DC/DC converter

Battery SOC (%)	Input parameters recorded in power logger			Output parameters measured using multimeters			
	Voltage $V_{dc, in}$	Current $A_{dc, in}$	Active power in (W_{dc})	Voltage out ($V_{dc, out}$)	Current out ($I_{dc, out}$)	Power out ($W_{dc,out}$)	Adapter Efficiency ($W_{dc,out}/W_{dc,in}$)*100
0	349.98	0.026	9.099	4.8	1.14	5.472	60%
25	349.96	0.027	9.449	4.8	1.06	5.088	54%
50	350.06	0.027	9.452	4.8	1.03	4.944	52%
75	350	0.022	7.7	4.8	0.81	3.888	50%
100	350	0.012	4.2	5	0.3	1.5	36%

All the input data for the different devices gathered and discussed in this section are arranged in individual excel files. The different parameters arranged in excel files are duration, percentage (battery SOC), voltage, current, active power, apparent power, reactive power, active energy, apparent energy, reactive energy, power factor, conversion losses, line losses, conversion energy losses and line energy losses. These parameters along with randomization methodology discussed in chapter 3 are used for the obtaining a year-long load profile. From which the overall active energy consumption (kWh/year), conversion energy losses (kWh/year) and line energy losses (kWh/year) are analyzed which will be discussed in the following.

3 GENERATING YEAR LONG LOAD PROFILE

To validate the technical potential of a LVDC grid, a full year load profile is necessary. This chapter summarizes the methodology utilized to develop a full year load profile for the DC Office setup and discusses the technical potential and energy savings of the LVAC and LVDC grids installed in the DC Office project.

To determine the performance and the efficiency of the LVDC grid, a full year load profile of the DC Office setup is necessary. Metering the setup will assist to develop a full year load profile. However, metering the DC Office set-up for whole year will be expensive and cumbersome. Thus, to determine a full year load profile for DC Office set-up, the electrical parameters measured in chapter 2 are extended to a full year using a program in Matlab.

Section 3.1 explains the methodology utilized to randomize the electrical parameters based on a real-time scenario. Section 3.2 summarizes the variation of the active energy consumption (kWh/year) for lighting, laptops and mobile phones for a full year. Further, section 3.3 gives the sensitivity analysis for randomization. Section 3.4 evaluates the performance of the LVDC grid system using different cases and section 3.5 gives the energy savings of the LVDC grid compared with the LVAC grid.

3.1 RANDOMIZATION METHODOLOGY

The electrical parameters measured while charging the loads (Laptops and Mobile Phones) from 0% to 100% battery SOC are utilized to develop a full year load profile for the DC Office setup. The measurement technique used to measure the electrical parameters of the loads is discussed in chapter 2. The same randomization methodology is used for both the LVAC and LVDC grids. In order to develop a full year load profile in accordance with a real-time scenario, the following randomization methodologies are utilized [3][14]:

- Randomization for the loads (Laptops and Mobile-Phones)
- Randomization of loads Plug-in Time
- Randomization of loads Plug-out Time
- Randomization of loads Battery percentage (SOC) during Plug-in

Since DC Office is closed on weekends, the randomization of the loads is performed only for working days.

3.1.1 Randomization for the loads

As described in chapter 2, the electrical parameters while charging the loads (Laptop 1, Laptop 2 and a Mobile-Phone) are measured using devices mentioned in Table 2.6. It was observed that maximum 10 laptops and 2 mobile phones were utilized for charging at the DC Office. However, in reality all the 10 laptops and 2 mobile phones will not be connected for charging at the same time. Thus, to replicate a real-time scenario, the number of active loads (Laptops and Mobile Phones) per day are randomized for a full year as shown in Figure 3.1. For lighting in LVAC grid, there are 32 tubelights and in the LVDC grid there are 16 LED lights, these lighting loads are observed that it is turned-ON throughout the office working hours (8:00 AM to 6:00 PM). As discussed in section 2.4, half the number of LED lights are sufficient to provide illumination replacing tubelights.

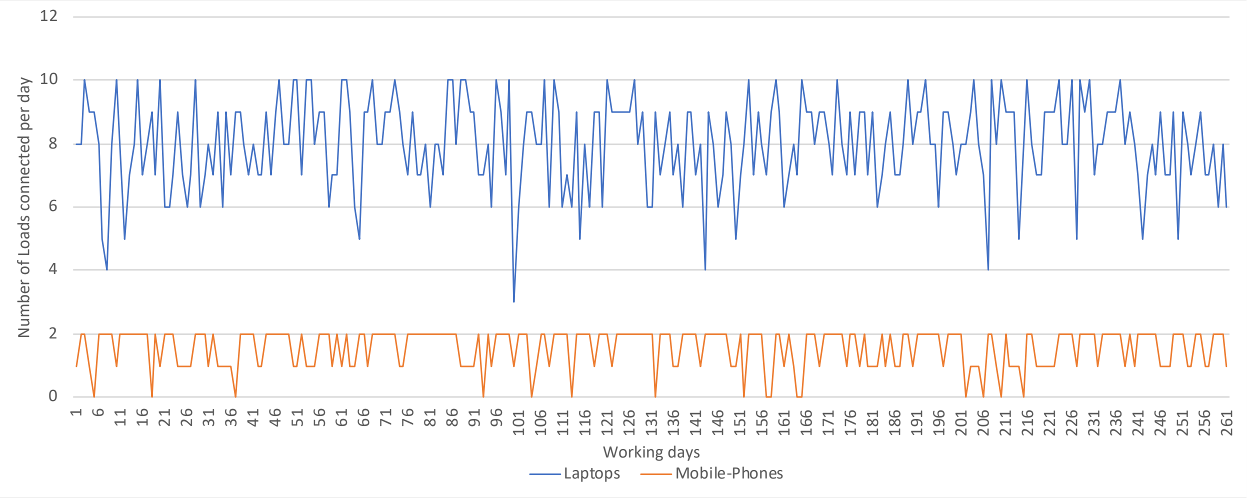


Figure 3.1: Randomization of loads

Due to unavailability of 10 different laptops with USB – C facility to measure the electrical parameters in both the LVAC and LVDC grid system, only two laptop categories (Laptop – 1, Laptop – 2) are used to measure, and it is assumed that 5 laptops belong to Laptop-1 category and another 5 laptops belong to Laptop-2 category. Likewise, it is assumed there are only 2 Mobile-Phones used for charging in LVAC and LVDC.

3.1.2 Randomization of the loads Plug-in Time

Randomization of load’s plug-in time is necessary to replicate the real-time scenario while developing a full year load profile. The randomization occurs for all the 12 loads individually, for example only 5 loads are shown here. Figure 3.2 shows the variation in plug-in time for five loads. Load-1 and load-2 belongs to laptop-1 category; load-3 and load-4 belongs to laptop-2 category; and load 5 belongs to Mobile-Phone category. Since, the DC Office opens at 8:00 AM in the morning, the loads plug-in time commences only from 8:00 AM as observed in Figure 3.2. The

Figure 3.3 shows the variation in plug-in time for the mentioned 5 loads during the month of January.

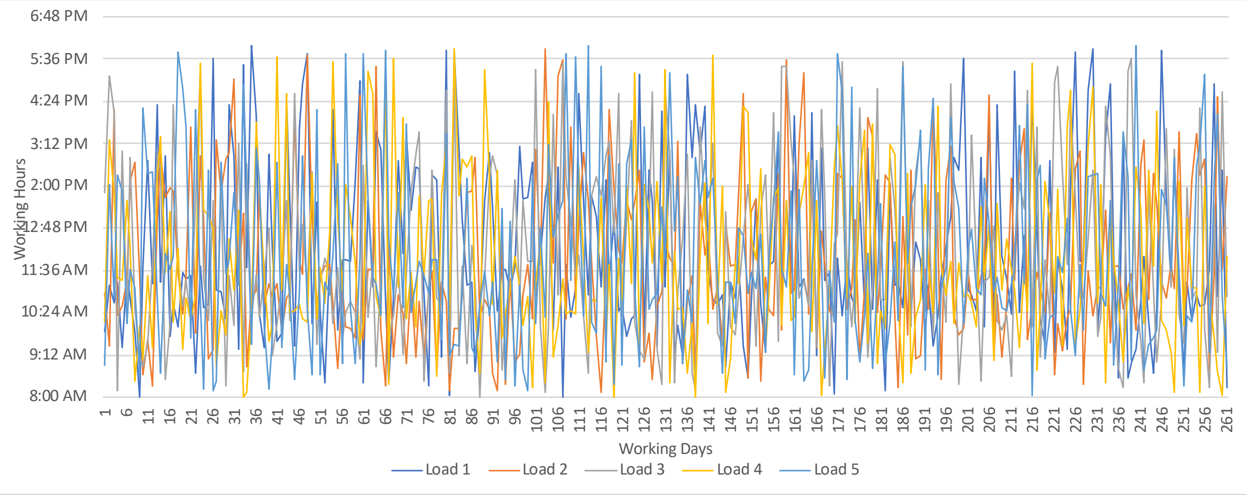


Figure 3.2: Randomization of loads Plug-in time for a year

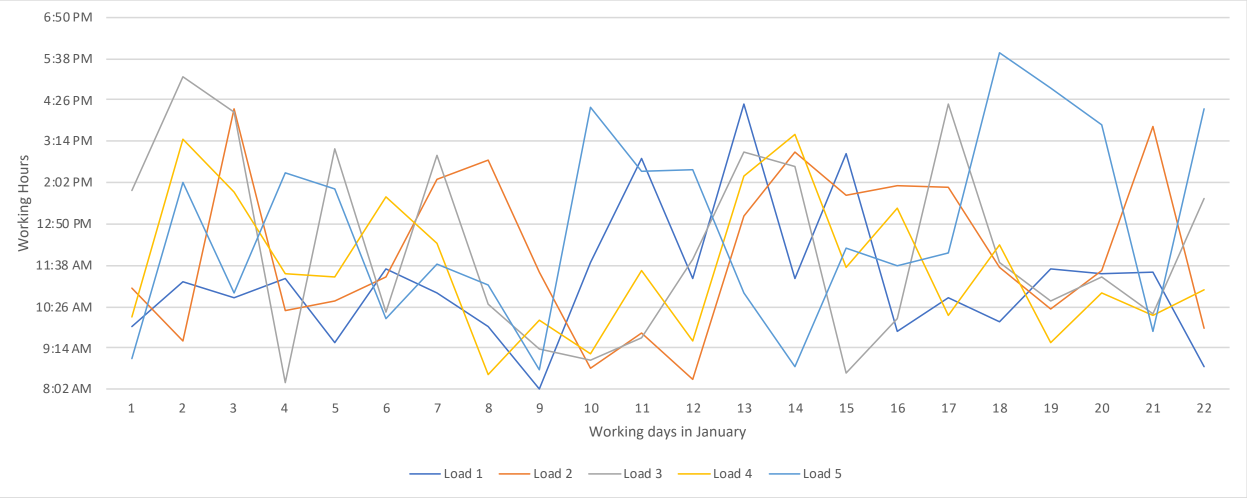


Figure 3.3: Randomization of loads Plug-in Time for the Month of January

3.1.3 Randomization of the loads Plug-out Time

Considering the opening hours of the DC Office (from 8:00 AM to 6:00 PM), the plugged-in loads can be plugged-out at any time within the office hours. Thus, to replicate the real-time scenario the plug-out time of the loads is randomized. Figure 3.4 shows the variation in plug-out time for five loads: load-1 and load-2 belongs to laptop-1 category; load-3 and load-4 belongs to laptop-2 category; and load 5 belongs to Mobile-Phone category. Figure 3.5 shows the plug out time for the mentioned 5 loads during the month of January.

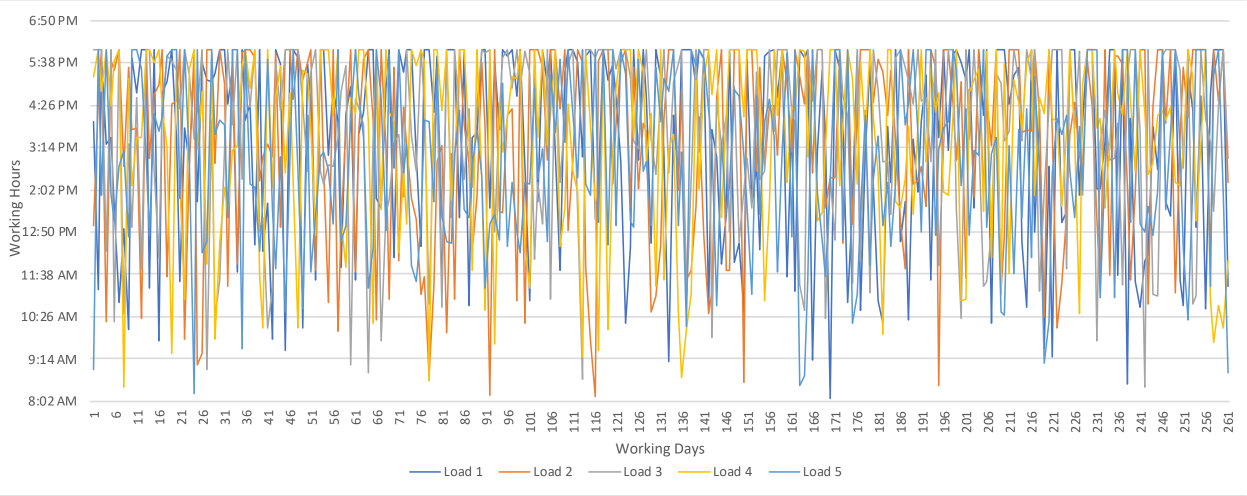


Figure 3.4: Randomization of loads Plug-out time for a year

Figure 3.5: Randomization of loads Plug-out time for the Month of January

3.1.4 Randomization of Loads Battery Percentage (SOC) during Plug-In

The electrical parameters measured while charging the loads vary with the battery percentage (SOC). Thus, it is significant to incorporate the 'randomization of the loads battery percentage (SOC) during plug-in. Figure 3.6 shows the variation in battery percentage (SOC) during plug-in for load 1. Likewise, the battery percentage (SOC) is randomized for all the 10 laptops and 2 Mobile-Phones individually.

A year-long load profile was developed using Matlab and the flow chart of the algorithm is shown in Figure 3.7 below. From which, the randomized year-long profile is discussed in section 3.2.

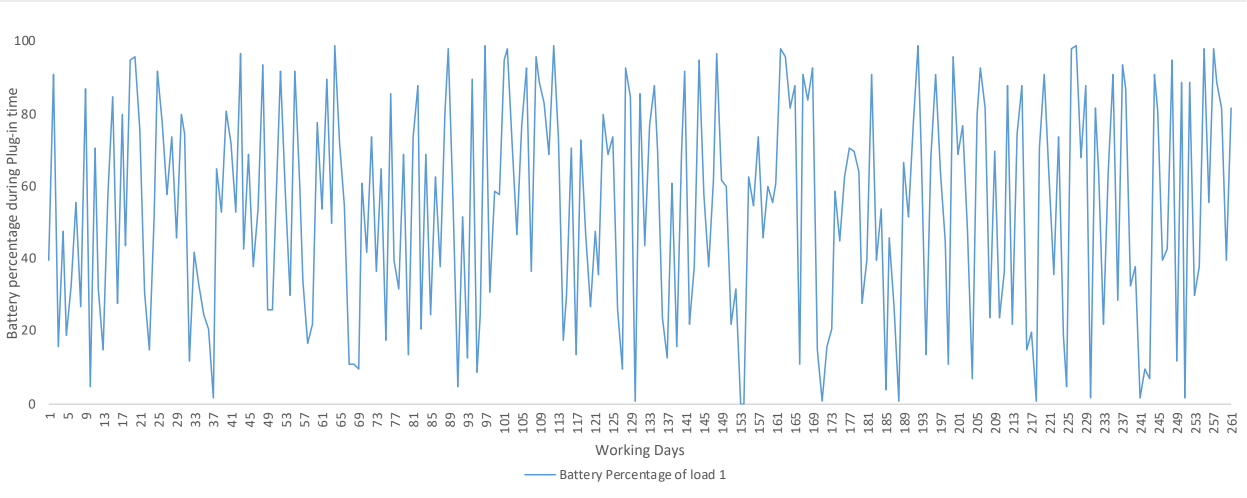


Figure 3.6: Variation in Battery percentage (SOC) during plug-in time for load 1

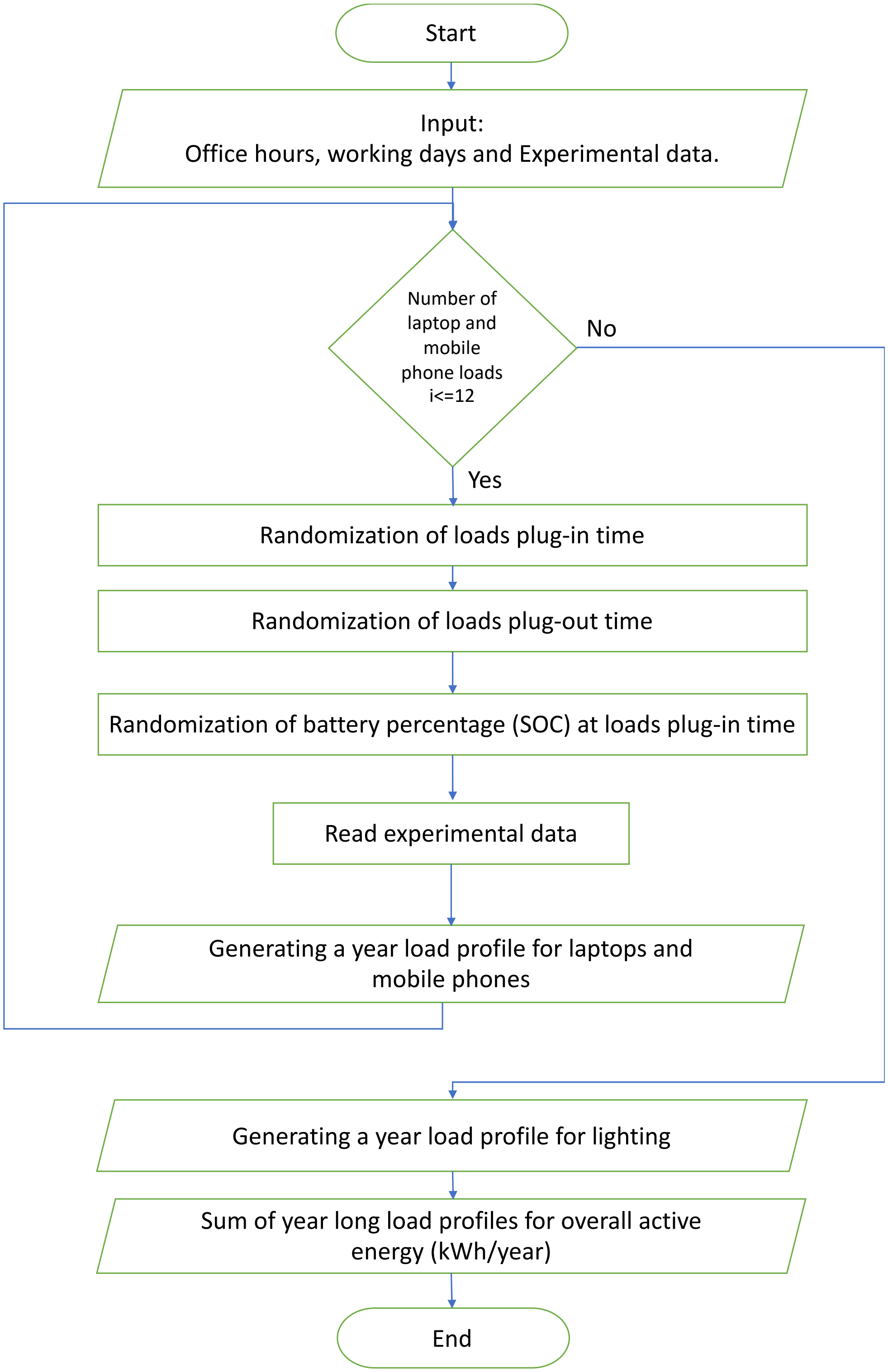


Figure 3.7: Matlab Flow chart

3.2 YEAR LONG PROFILE FOR ACTIVE ENERGY CONSUMPTION (kWh/day)

The randomization methodology is further utilized to determine a year-long load profile for both the LVAC and LVDC grids. In-order to show comparison between these systems, the data obtained are shown in graphs below for lighting, laptops and mobile phones. As discussed in section 2.4, active energy (kWh) is considered to compare both grids.

The Figure 3.8 shows a year-long active energy consumption (kWh/day) for lightings. The graph is constant for lighting because it is assumed that lights are turned-ON throughout the office time.

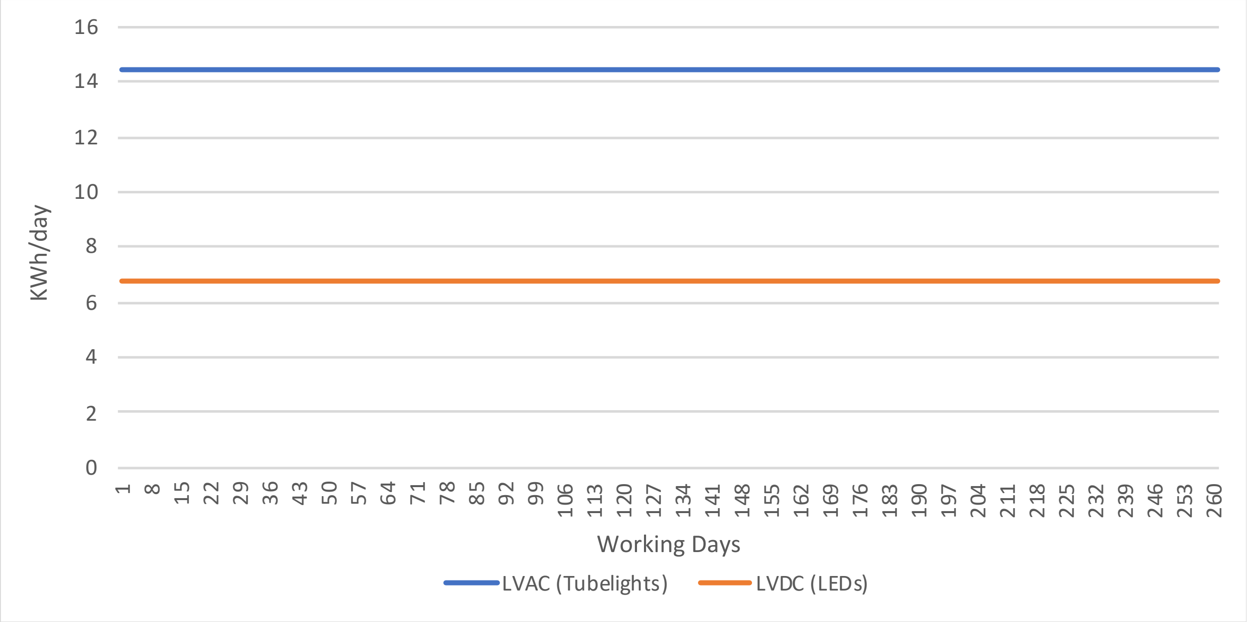


Figure 3.8: Year-long profile active energy consumption (kWh/day) for lightings in LVAC and LVDC

The Figure 3.9 shows a year-long active energy consumption (kWh/day) randomized for all 10 laptops. Following which, the Figure 3.10 shows the active energy consumption (kWh/day) for all 2 mobile phones used in a year. Using these data, the section 3.5 will discuss about the technical potential comparing LVDC grid with LVAC grid.

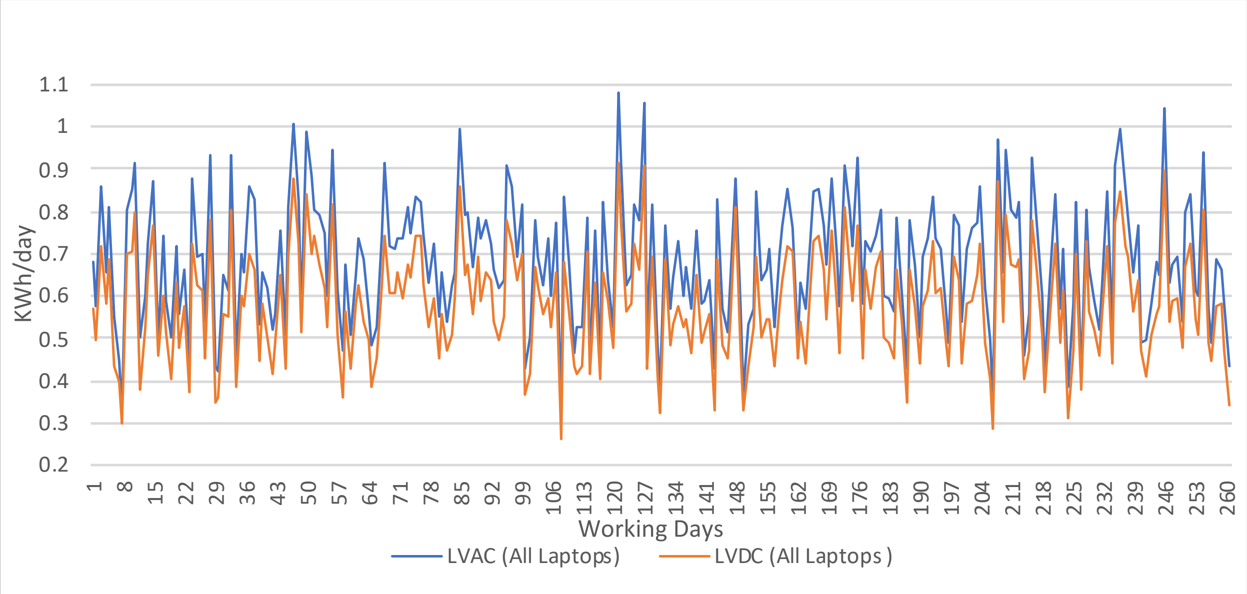


Figure 3.9: Year-long profile active energy consumption (kWh/day) for all laptops in LVAC and LVDC

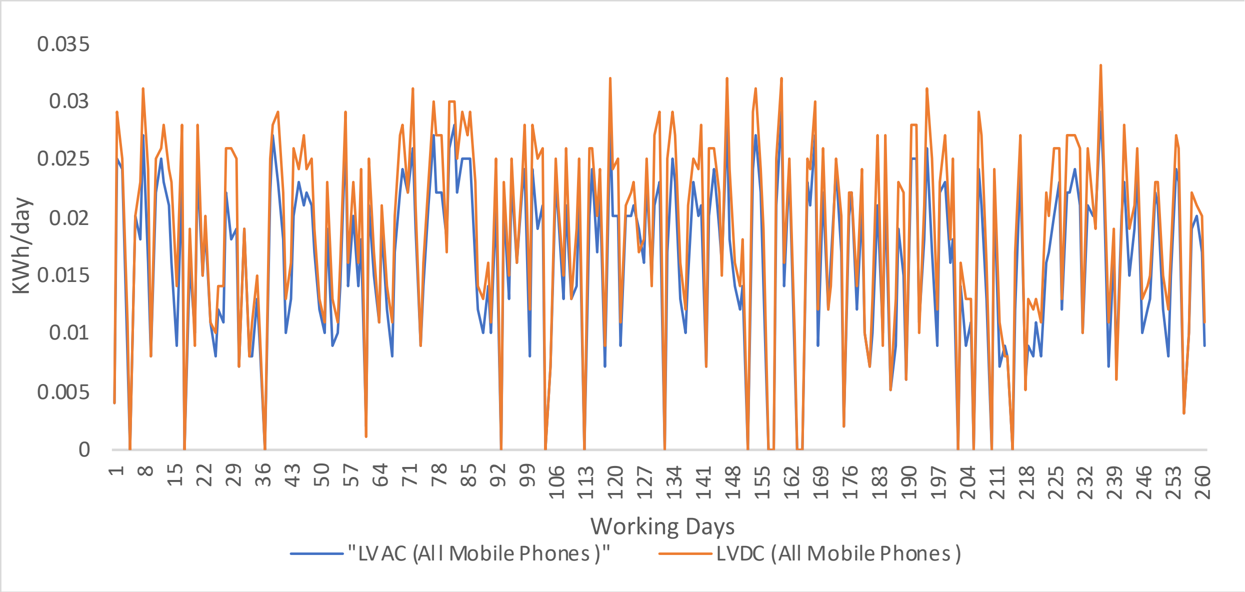


Figure 3.10: Year-long profile active energy consumption (kWh/day) for all Mobile Phones in LVAC and LVDC

3.3 SENSITIVITY ANALYSIS FOR RANDOMIZATION

The randomization methodology is used to generate year-long data for comparison of the LVAC and LVDC grids in the DC Office. Keeping the input measurements and randomization methodology same, the randomizer should randomize nearly the same overall active energy consumption (kWh/year). So, in order to check the randomization, a sensitivity analysis is carried out.

The randomizer is run for several times and the results of overall active energy consumption LVAC grid are shown in Figure 3.11. In this 11-consecutive randomization, the maximum result is

3946.479 kWh/year and minimum result is 3935.73 kWh/year. The difference of the maximum and minimum results is negligible per year and did not differ much. Therefore, we conclude that the randomizer has a minimal influence on the results that are analyzed in section 3.4 and section 3.5.

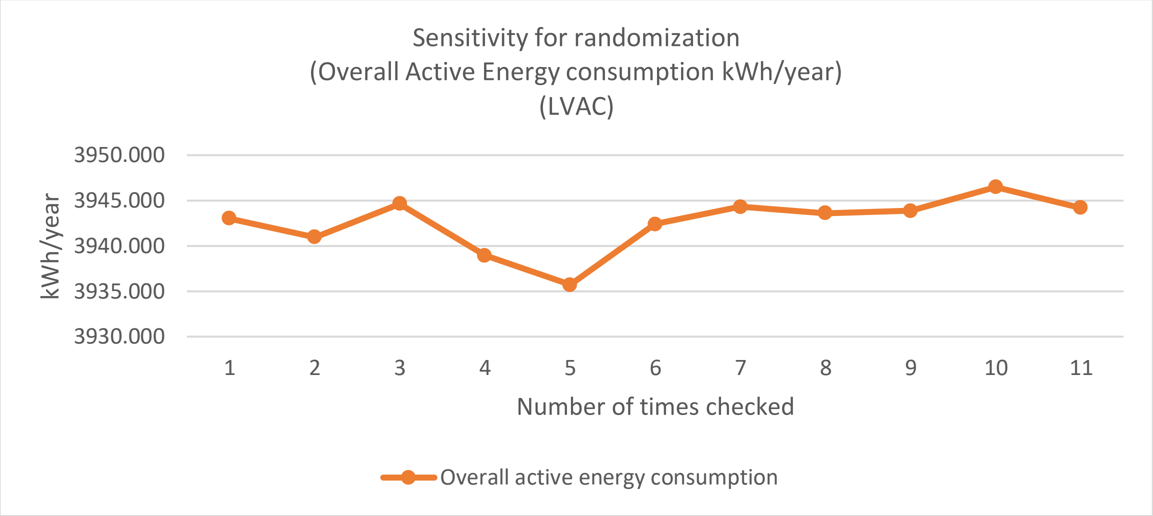


Figure 3.11: Randomization sensitivity

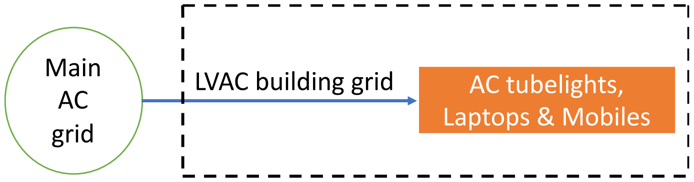
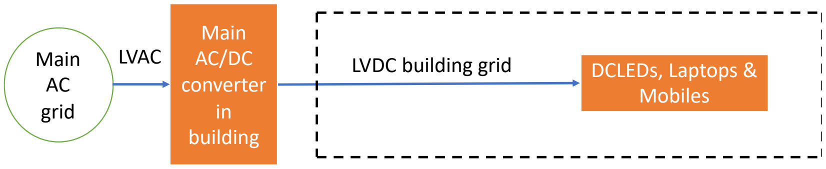
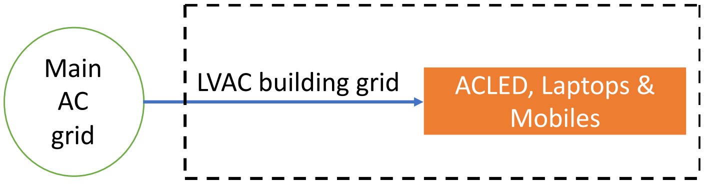
From these set of iterations, the mean value 3944 kWh/year is selected for the technical analysis of the LVAC grid and similarly the randomizer is executed for several times in LVDC case and the mean value of 1931 kWh/year is chosen. As discussed in section 2.3, the accuracy of the measurement devices is ± 0.5%. Considering the measurement device's accuracy along with the selected kWh/year values, the sensitivity of the results is between (3944 ± 20) kWh/year or (1931 ± 10) kWh/year.

3.4 TECHNICAL POTENTIAL and ANALYSIS

From the experimental measurements and randomization methodologies, the previous sections explained the applied year-long load profile generation. In-order to analyze the results from randomization, three different cases are formulated as shown in Table 3.1. The ACTube and DCLED cases are obtained from the LVAC and LVDC experimental results and randomization. The ACLED case is formulated in-order to neglect the energy savings obtained by using LED technology which is further explained in section 3.4.3. These cases explain:

- Energy savings that are obtained by replacing the LVAC grid with a LVDC grid in DC-Office.
- The overall efficiency of the LVAC and LVDC grids
- Conversion and line energy losses for all the loads utilized in LVAC and LVDC.

Table 3.1: Different cases for technical potential and discussion

<table>
<tr>
<td>ACTube case</td>
<td>
</td>
<td>LVAC experiment</td>
</tr>
<tr>
<td>DCLED case</td>
<td>
</td>
<td>LVDC experiment</td>
</tr>
<tr>
<td>ACLED case</td>
<td>
</td>
<td>Assumption</td>
</tr>
</table>

As discussed in section 2.2.1, for obtaining the overall efficiency of the LVAC and LVDC grids, the following equation is used [15].

$$Overall\ efficiency\ of\ grid = 100 * \left(1 - \frac{E\ losses\ (kWh)}{E\ load\ (kWh)}\right)$$

3.4.1 ACTube case:

According to the year-long randomization of the LVAC grid, 250 m^2 DC Office consumes an overall active energy of 3944 kWh/year which includes lighting (tubelights), laptops and mobiles and its corresponding losses. The Figure 3.12 below shows the overall active energy consumption and share of both conversion losses and line losses.

The overall conversion energy losses and line energy losses are 379 and 88 kWh/year, respectively, which corresponds to 9.61% and 2.23% of the overall active energy consumption. From this, the overall efficiency of the LVAC grid is 88.16%.

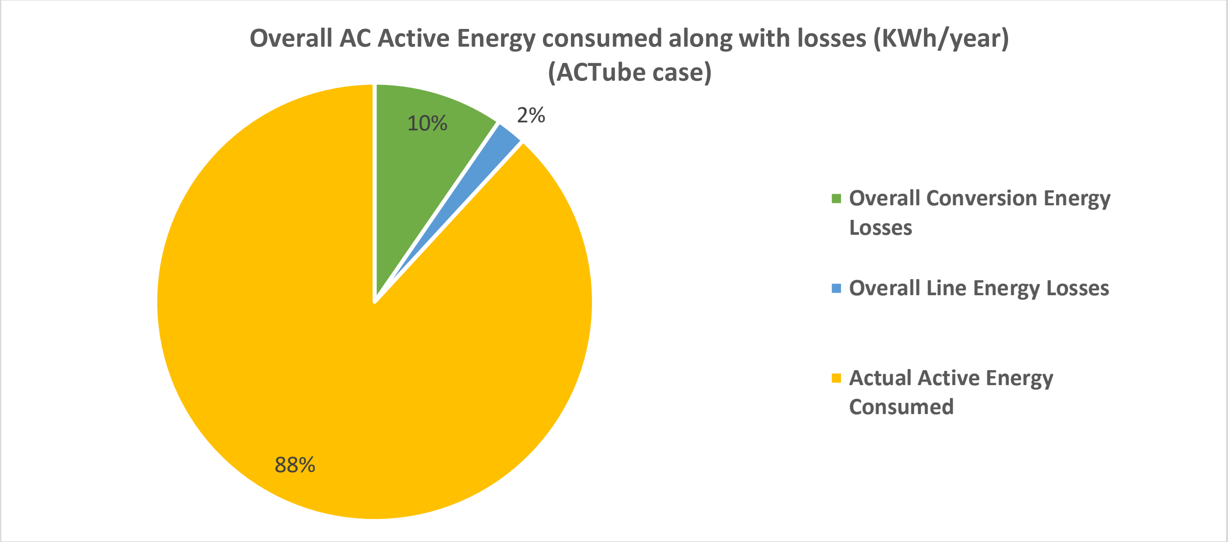


Figure 3.12: Overall LVAC Active Energy consumed along with losses (kWh/year) (ACTube case - LVAC experiment)

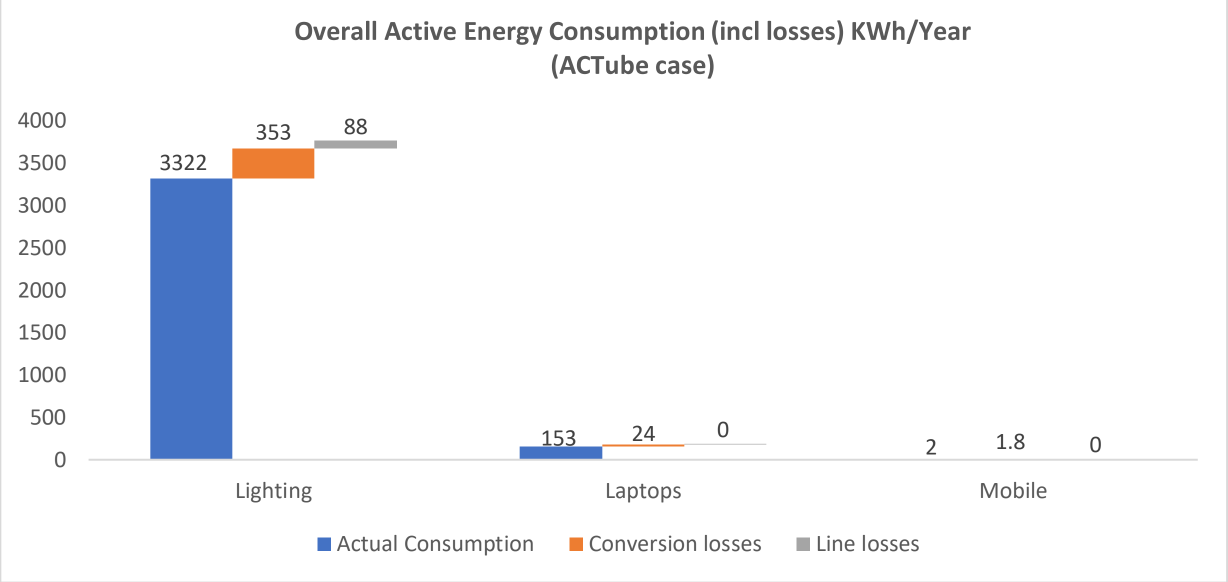


Figure 3.13: Overall LVAC active energy consumption with losses (kWh/year) individually for loads (ACTube case - LVAC experiment)

The share of overall active energy consumption by tubelights, laptops and mobile phones along with losses is shown in Figure 3.13. The tubelights individually consume 3763 kWh/year (95.41%) of overall active energy including losses. In which, the conversion energy loss of tubelight is 353 kWh/year (9.38%) and line energy loss is 88 kWh/year (2.34%).

When considering laptops, it consumes 177 kWh/year (4.49%) of overall active energy. In this, the conversion losses are 24 kWh/year (13.56%) and line energy losses are very negligible (0.326 kWh/year). Among all the devices, mobiles consume least amount of energy, 3.8 kWh/year

(0.1%) of overall active energy. In this, 1.8 kWh/year (47.37%) of energy is lost in conversion and nil line energy losses.

3.4.2 DCLED case:

From the randomization results, the LVDC grid in the DC Office consumes overall active energy of 1931 kWh/year which includes lighting (DC LED), laptops and mobiles. The Figure 3.14 shows the share of overall active energy consumption. The overall conversion energy losses are 94 kWh/year (4.87%) whereas overall line energy losses are 6 kWh/year (0.311%). From this share, the overall efficiency of the LVDC grid is 94.82%.

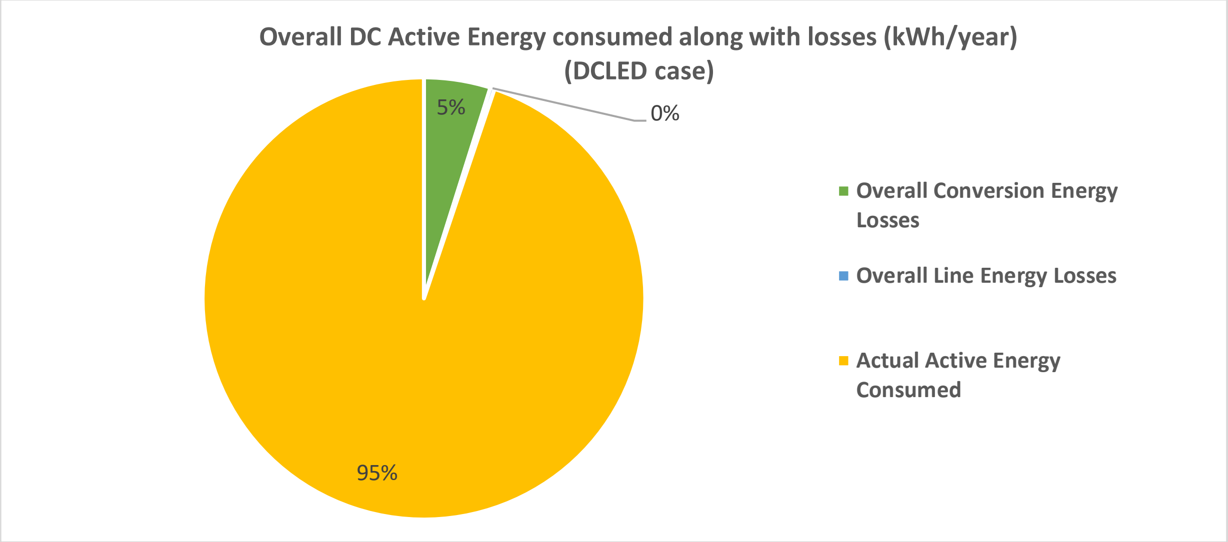


Figure 3.14: Overall LVDC Active Energy consumed along with losses (kWh/year) (DCLED case - LVDC experiment)

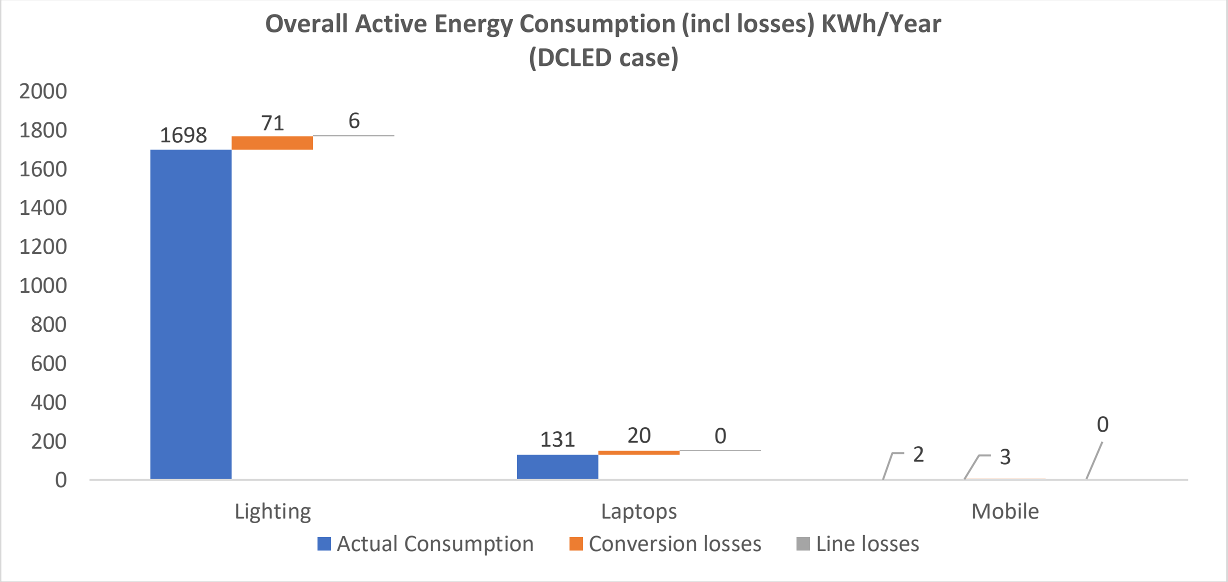


Figure 3.15: Overall LVDC active energy consumption with losses (kWh/year) individually for loads (DCLED case - LVDC experiment)

Figure 3.15 shows the individual energy consumption of DC LEDs, laptops and mobiles in LVDC setup. The DC LEDs consume 1775 kWh/year (91.9%) of overall active energy. In this energy consumed by LVDC lightings, the conversion loss is 71 kWh/year (4%) and line energy losses is 6 kWh/year (0.338%).

Similarly, laptops consume 151 kWh/year (7.8%) of overall active energy among which the conversion energy losses are 20 kWh/year (13.25%) and line energy losses are negligible (0.022 kWh/year). The least consumed device is mobiles which consumes 5 kWh/year (0.259%) of the overall active energy consumption. In this 5 kWh/year, the conversion energy lost is 3 kWh/year (60%) and the energy lost in line is nil.

3.4.3 ACLED case:

In both $230V_{ac}$ and $350V_{dc}$ experimental setups, the lighting is the major load following the laptops and mobiles. In principle, the LED lighting consumes less energy compared to the tubelights. As a main difference in these setups, the tubelights are used in AC for lighting whereas the LEDs are used in DC. With the results obtained from these setups, in the ACTube case, the overall active energy consumption is 3944 kWh/year and in DCLED case is 1931 kWh/year. From these results, it can be seen that DC setup consumes 2013 kWh/year less than AC setup. But in this result, the energy saved from LED technology compared to tubelights is also included. This makes the result complicated to draw a conclusion. In-order to overcome this complexity, this ACLED reference case is formulated.

In this reference case, the tubelights are considered to be replaced by LEDs which operate in AC. From the experimental reference of Fraunhofer [16], it is considered that LED consumes $0.9W_{dc}/m^2$/100Lux in AC and 0.87 W_{dc}/m^2/100Lux in DC. From the outcome of the experiment by Fraunhofer, LEDs consume $0.03W/m^2$/100Lux in AC higher than DC.

In-order to make use of this data in the DC office setup, the area of DC office and the Lux required are measured. The average lux is approximately 700 Lumens which is measured for LEDs in DC and the area is 250 m^2. From these data, the input file for ACLED lighting is prepared. For the DC office setup, the difference in power of ACLED with respect to DCLED is given by $0.03\ W*250m^2*7 = 52.5\ W$. Also, from the measurements and randomization, LEDs in the DC office will consume 693.5 W_{dc} (for 16 LEDs). From this value, the addition of 52.5 W i.e. $693.5\ W_{dc}+52.5\ W = 746\ W_{ac}$ gives the power used by ACLEDs if installed in DC Office.

From this assumption and the randomization methodologies, it is calculated that the LED lightings in AC consumes 1909 kWh/year of overall active energy. Theoretically for an identical load, there should be a similar amount of actual active energy consumption both in AC and DC. For which, it is considered that the ACLED lightings also have actual consumption 1698 kWh/year same as DCLED lightings.

After this consideration, both conversion and line energy losses for ACLED lightings are calculated as 211 kWh/year. Meanwhile for the ACLED case, the laptops (177 kWh/year) and mobiles (3.8

kWh/year) are kept the same as measured in ACTube case (see Figure 3.13). Now, the overall active energy consumption in the ACLED case is 2090 kWh/year.

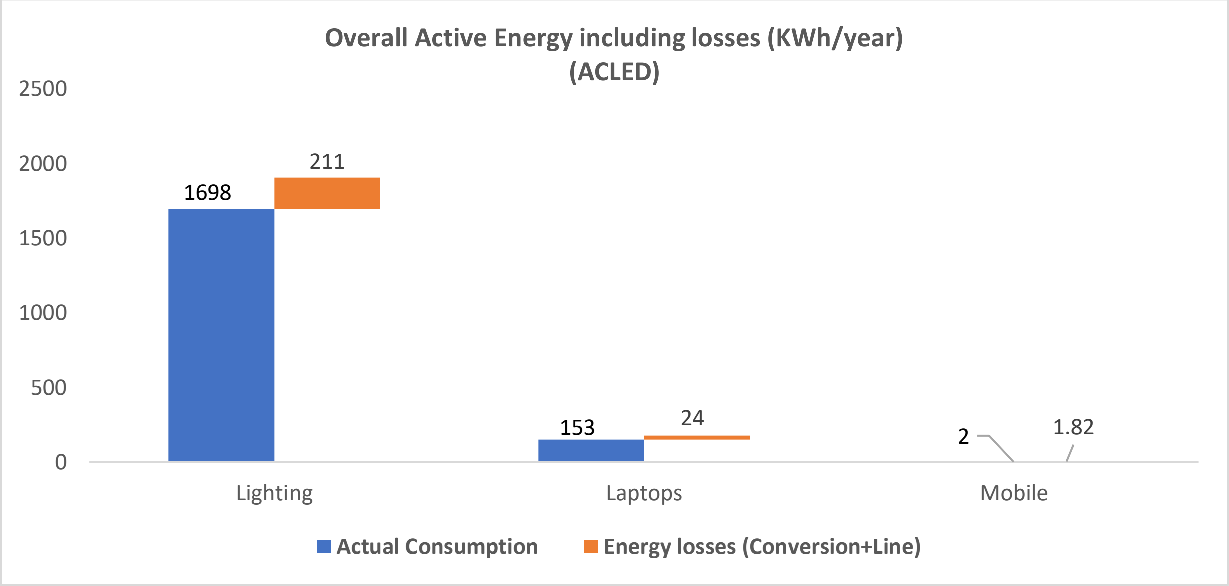


Figure 3.16: Overall LVAC active energy consumption with losses (kWh/year) individually for loads (ACLED case - LVAC LED assumed)

Figure 3.16 shows the overall consumption of ACLEDs, laptops and mobile phones. The ACLED lighting consume 1909 kWh/year (91.34%) of overall active energy consumption. Furthermore, laptops and mobile phones consume 177 kWh/year (8.47%) and 3.82 kWh/year (0.183%) of overall active energy consumption.

When only AC LED lighting is considered, the conversion and line energy losses are 211 kWh/year (11.05%) from 1909 kWh/year. When considering Laptops, they consume 177kWh/year (8.47%) of overall active energy consumption, in which the energy losses are 24 kWh/year (13.56%). For mobile phones they consume 3.82 kWh/year (0.183%) among that 1.82kWh/year (47.64%) is the energy losses.

3.5 Discussion and analysis of different cases:

3.5.1 ACTube vs DCLED

This section discusses the LVAC and LVDC grids from the results obtained in ACTube and DCLED cases. From the results, it is observed that the overall efficiency of the LVDC grid is 6.7% higher than the LVAC grid for small buildings similar to the DC Office setup.

When considering the devices individually, the conversion energy losses for laptops are low in LVDC compared with LVAC grid. But for Mobile Phones, the conversion energy losses are higher in LVDC than LVAC. This is because the DC/DC converter used in the LVDC grid is a prototype. It was informed by the Direct Current B.V. that with the upcoming DC/DC converter prototype models the internal designs will be altered for better efficiencies lowering the conversion energy losses. Also, looking closely at the variable laptops and mobile phone loads in Figure 3.13 & Figure 3.15. The actual energy consumption is high in ACTube compared to DCLED case. A difference of 22kWh/year can be observed. Since, rectified AC can contain voltage ripples and higher order harmonics from which a difference in actual consumption of AC and DC is observed.

On the other hand, the line energy losses for laptops and mobiles depends on current carried in the wires for both LVAC and LVDC. This line loss is negligible when only 10 laptops and 2 mobiles are considered in small buildings.

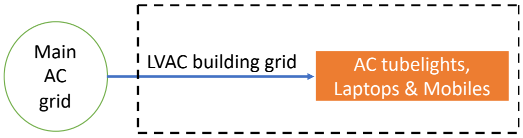
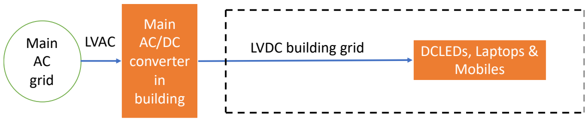
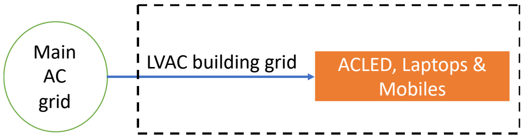
Lighting is the major load for small office buildings in both grids. It has lower percentage of conversion losses compared to laptops and mobiles because it functions at constant load with high efficiency throughout the operation. But for line energy losses, it draws more current and so, it has higher percentage of line losses compared to laptops and mobiles.

3.5.2 ACLED vs DCLED

From the comparison between the DCLED case and the ACLED case, overall efficiency of the ACLED case system is 88.67% and the overall efficiency of the DCLED case is 94.82% (from Equation 4). This comparison of results show LVDC grid is 6.15% more efficient than the LVAC grid when LEDs are used in both LVDC and LVAC grid.

When considering the energy savings for these two cases with the ACTube case as reference, the ACLED case saves 1854 kWh/year and DCLED case saves 2013 kWh/year. These savings from the above cases are done for the LVAC and LVDC grids represented in dotted lines shown in Table 3.2.

Table 3.2: Energy saving (kWh/year) for different cases

Cases	Single line diagram (Dotted box – considered system)	Energy consumption (kWh/ year)	Energy savings (kWh/ year)	% Savings
ACTube case (Experimental)		3944 (Reference value)	-	-
DCLED case (Experimental)		1931	2013	51%
ACLED case (Assumed for LED lights)		2090	1854	47%

From the experimental results of the cases from DC Office setup, if a LVAC grid (ACTube case) is replaced with a LVDC grid (DCLED case), then the energy savings achieved will be 51% along with 6.7% increase in overall system efficiency. Also, if the ACTube case (LVAC) is replaced with the assumed ACLED case (LVAC), the energy savings of 47% can still be achieved, but only 0.51% increase of overall system efficiency can be observed. In comparison between ACLED case (LVAC) and DCLED case (LVDC), the energy savings of LVDC grid is 4% higher and the overall system efficiency of LVDC is 6.15% higher.

From all the comparison between the technical potential cases, it can be clearly seen that the energy savings and overall efficiency of the LVDC grid system is higher than LVAC grid system.

4 COST SAVINGS AND MATERIAL COMPARISON

"What is the cost-savings of LVDC grid in DC office setup replacing LVAC grid?"

This chapter discusses the total investment cost savings (€) and total energy cost savings (€/12 years). The energy savings obtained and analyzed in the previous chapter is used in this chapter to find the cost savings of the LVDC grid replacing the LVAC grid. In addition, a discussion on the usage of copper and aluminium as conductor materials in a small building is performed.

The advantages of using LVDC grid in buildings replacing LVAC grid are due to the energy savings, material savings and development in Distributed Generation [17]. In chapter 3, the technical potential of the LVDC grid in the DC Office explained the energy savings for different cases. In this chapter, section 4.1, the cost savings for LVDC grid in the DC Office is discussed based on investment costs and energy savings. Section 4.2 compares copper and aluminium as conductor materials in LVAC and LVDC grids for the DC Office setup.

4.1 COST SAVINGS

The Loads used in the DC office are given in Table 4.1 and the energy savings (kWh/year) obtained for these loads in different cases are shown in Table 3.2.

Table 4.1: Number of loads used in DC office setup

Loads	Number of loads
Tubelights (LVAC)	32
LEDs (LVDC)	16
Laptops (LVAC & LVDC)	10
Mobile phones (LVAC & LVDC)	2

For the experiments, LEDs are used for LVDC (DCLED case), tubelights are used for LVAC (ACTube case) whereas Laptops and mobile phones are used in both cases. Among these loads, LEDs have a lifetime of 30000 hours [18] which is two times of tubelights lifetime (15000 hours) [19]. Considering the working hours of the DC office per year given in Table 4.2, the actual lifetime of installed LEDs is calculated to be around 12 years. This LEDs lifetime is assumed to be the lifetime of the DC Office system for the investment cost (€) calculations.

Table 4.2: Lifetime of the DC Office system

LEDs lifetime (hours)	30000
Office working hours/day	10
Working days/year	262
Lifetime of the system (years)	12

During the lifetime of the system, tubelights in the DC Office have to be changed twice in the LVAC grid due to its lifetime (30000 hours). The calculation for 32 tubelights in LVAC and 16 LEDs in LVDC that need to be changed in a period of 12 years are shown in Table 4.3. Likewise, due to malfunctioning and internal components ageing [20], the AC/DC and DC/DC converters (12 each) required for laptops and mobile phones are assumed to be replaced once in 12 years as shown in Table 4.4. The replacement of these converters and tubelights along with the following assumptions are used to calculate the total investment cost (€) and total energy consumption cost (€/12 years).

Table 4.3: Number of lights to be used during Lifetime of the DC Office system

Light Loads in DC Office	Replaced lights in DC Office/12 years
Tubelights	64
LEDs	16 (no change)

Table 4.4: Number of converters to be used during Lifetime of the DC Office system

Converters in DC Office	Number of converter in DC Office/12 years
AC/DC converter	24
DC/DC converter	24

For obtaining the investment cost and total energy consumption cost, apart from the above considerations, certain assumptions are considered as follows:

1) The cost of electric cables used is the same for both LVAC and LVDC.
2) The price of electricity, 0.11 €/kWh [21], is based on the energy consumption range of 1500 kWh to 5000 kWh from Eurostat data for the year 2017. This energy price is considered without taxes and considered to be constant throughout the lifetime of the system.
3) The commissioning and maintenance costs are considered the same for both LVAC and LVDC cases.

For comparison, the total energy cost savings (€/12 years) and payback period (years) are calculated by replacing ACTube case (LVAC) either with DCLED case (LVDC) or with ACLED case (LVAC). A detailed cost calculation for each case considered the number of loads and the assumed conditions is presented in Table 4.5.

4.1.1 ACTube (LVAC) replaced with DCLED (LVDC)

From experiment conducted, lighting energy consumption for LVDC case is calculated to be 21300 kWh/12 years, whereas for LVAC grid the lighting energy consumption is 45156 kWh/12 years. A distinct difference of energy savings is observed from these values. Similarly, for laptops and mobile phones, the energy consumption in case of LVDC is calculated as 1872 kWh/12years. In the DC Office setup for LVAC case, the energy consumption for Laptops and mobile phones is 2172 kWh/12 years. These discussed values are highlighted using yellow in the Table 4.5.

From the Table 4.5, investment cost (€) for lighting in LVDC case is observed to be 125% more than the LVAC case over 12 years due to higher cost of LEDs. For laptops and mobile phones, the investment cost (€) for LVDC case is 31% cheaper than LVAC case. (the values are highlighted using green)

In the same table, the total energy cost savings of the DC office setup is also discussed when replacing ACTube (LVAC grid) with DCLED (LVDC grid). From the results shown in Table 4.5, it can be clearly seen that by replacing LVAC with LVDC in small buildings those similar to DC Office setup, reduced the total investment costs (€) (for 12 years) by 28%. Also, it has increased total energy cost savings (€/12years) by 51%, therefore, achieving the payback period in 6 years.

Table 4.5: Cost savings of cases replacing ACTube case (LVAC):

Life time of system = 12 years	**ACTube case (LVAC experiment)**	**DCLED case (LVDC experiment)**	**ACLED case (LVAC assumed)**
Lightings			
Cost per light €	1.5	7.5	7.5
Life time (hours)	15000	30000	30000
Lights replacement during lifetime of system	64	16 (no change)	16 (no change)
Lighting investment cost (€) (for 12 years)	96	120	120
Lighting energy consumption (kWh/year)	3763	1775	1909
Lighting energy consumption (kWh/12 year)	45156	21300	22908
Laptops and mobile phones			
AC sockets (12 sockets) (€ 5/socket) (for 12 years)	60	-	60
Converter (€/24 converters) (for 12 years)	1680 (€70/(AC/DC) converter)	1200 (€50/ (DC/DC) converter)	1680 (€70/ (AC/DC) converter)
Sockets & converters investment cost (€) (for 12 years)	1740	1200	1740
Laptops and mobile phones energy consumption (kWh/year)	181	156	181
Laptops and mobile phones energy consumption (kWh/12 years)	2172	1872	2172
Cost savings			
Total investment cost (€) (for 12 year)	1836	1320	1860
Total energy consumption (kWh/12 years)	47328	23172	25080
Total energy cost (€/12 year) @ (€ 0.11/kWh)	5206.08	2548.92	2758.8
Total energy cost saving replacing ACTube case (€/12 years)	-	2657.16	2447.28
Total energy cost saving replacing ACTube case (€/year)	-	221.43	203.94
Payback period replacing ACTube case (years)	-	6	9

4.1.2 ACTube (LVAC) replaced with ACLED (LVAC)

As discussed earlier in section 3.4.3, replacing tubelights with LEDs in the LVAC grid also achieve energy savings. This section explains the total cost savings and payback period when ACTube is replaced with ACLED. The results from Table 4.5 show that the total investment cost (€) is increased by 101.3% and total energy cost savings is increased by 47% with a payback period of 9 years.

Comparing section 4.1.1 and section 4.1.2, it is estimated that the LVDC grid (DCLED case) has lower investment costs, higher energy savings and better payback period than LVAC grid. The total investment cost savings are higher in LVDC due to the lower price of DC/DC converters and LEDs longer lifetime. The DC/DC converters used in this experiment is a prototype and bulk manufacturing of these DC/DC converters can reduce the investment cost achieving shorter payback period than calculated.

4.2 COMPARISON BETWEEN COPPER AND ALUMINIUM

According to the international standard for electrical installation in buildings (IEC 60364), aluminium cables are not currently used due to physical damage and fire safety. Previously during 1960s, cheap EC grade aluminium wires where used for electricity supply in residential dwellings due to the high price of copper. But later it was realized aluminum may galvanize and was unsafe causing fire accidents which led copper as predominant electrical conductors for LV grids [22].

At present-day, several aluminium alloys (AA-8000 standard) with coatings are available in the market as electrical conductors and connectors in-order to avoid galvanization. In near future, from the research and installation procedures [23][24] there are opportunities for aluminium to replace the copper for LV electrical grids in the buildings. An explanation for electrical wire selection and properties of copper and aluminum are discussed in appendix B. Hereafter, the discussion will provide an overview of cost savings for the DC Office when copper and aluminum wires are used.

The usage of conductor materials in a LVAC grid and a LVDC grid is almost equal in small buildings, because the resistive losses in the wires are very small neglecting the skin effect in the LVAC grid. In that case, the cross-section area (mm^2) of the wire remains the same for the DC Office setup as explained in [25].

In the DC-office setup, for both AC and DC, 5 core*1.5 mm^2, multi-stranded and HFFR/XLPE insulation copper cables are selected. The specifications of these copper cables are as shown in Table 4.6 below.

Table 4.6: Specification of copper wire used in DC Office setup

Ampacity (A)	No of cores * area (mm^2)	Resistivity (Ohm/km)	kg/km
22	5 * 1.5	12.5	335

Now for comparison between copper and aluminum usage in LV electrical grids, it is considered that there is no compromise in energy savings and safety. In that case, the resistance, ampacity and insulation type of the aluminum wire should be the same as copper. For which, the aluminum cable selected for the DC office will be as shown in Table 4.7 according to the properties discussed in appendix B and the cable charts in [26] and [27]. For simplicity, the cost for aluminum and copper is considered as the metal prices/kg at Copper - € 5.87/kg and Aluminium - € 1.96/kg [28][29].

Table 4.7: Comparison between copper and aluminum as conductor materials for DC Office setup

AC and DC resistance (Ohm/km)	Ampacity (A)	Material	cable cross sectional area (mm^2) (5 core cable)	Length (m) (6 strings according to DC office design)	kg/(6*50 m)	Cost € /(kg/(6*50m))
12.5	22 A	Copper	1.5	6*50	100.5	589.94
	23 A	Aluminum	2,5	6*50	50.25	98.5

From the Table 4.7, it can be seen that for the same ampacity and resistance, the aluminum has twice less weight material usage and 6 times less conductor investment cost than copper [23]. Apart from the total investment cost (€) and total energy cost saving (€/12year) discussed in 4.1, the usage of Aluminium instead of copper will further decrease the investment costs which favours diffusion of LVDC grids in new buildings. Meanwhile, if the aluminum is incorporated in big buildings then, the initial investment cost savings may be drastically higher which have to explored in future research.

Hereafter, the scenario of LVDC grid systems in buildings in the Netherlands are studied under the topic commercial potential using the Function of Innovation Systems (FIS) approach.

5 COMMERCIAL POTENTIAL OF LVDC GRID INSIDE BUILDINGS

“What is the current market scenario for the LVDC grid systems for buildings in the Netherlands?”

In this chapter 5, the current scenario of the LVDC grid in the Netherlands will be identified using the Function of Innovation System (FIS) theoretical framework. Section 5.1 explains the criteria for the selection of the theoretical framework. Section 5.2 discusses the theoretical frameworks that can deal with the selection criteria. Section 5.3 briefs about the DC grid systems and the technology map. Section 5.4 identifies the current scenario of a LVDC grid in the Netherlands. Section 5.5 gives the drivers and barriers of the LVDC grid and section 5.6 gives the positive and negative feedbacks from the FIS framework using virtuous and vicious cycles.

5.1 Criteria for selection of framework:

A DC grid system inside buildings is essentially a status quo change where existing and new actors have to accept and adopt it. In-order to analyze this, a suitable approach is required for exploring the commercial potential of a DC grid system in the Netherlands. For this purpose, certain criteria have been set for selecting the framework.[30] The criteria are as follows:

1. **Technology specific:** The development and diffusion of the DC grid system in buildings is the focus of the research. The framework must provide space for technology specific research.

2. **Dynamic analysis:** As a DC grid is a change in status quo, the analysis must incorporate the dynamics of the system in-order to explain the diffusion and development of DC grids in buildings.

3. **Infrastructure:** The framework must allow to discuss about the current developments in technology and its related institutional settings for influencing the development and diffusion of the system.

4. **Allow for comparison between systems:** As explained, a DC grid system in buildings is a system change from the traditional AC grid system and the framework should allow for the comparison between the actors and stakeholders for both systems to make a proper comparison for diffusion.

5. **Linkage between the actors and stakeholders:** There are many actors and stakeholders responsible for a particular technology. Does the framework provide an interconnection between those actors and stakeholders in-order to study the market infrastructure?

6. **Wide analysis:** The other relevant factor such as rules, regulations, policies, subsidiary schemes, societal acceptance or resistance and many more should be allowed to be incorporated into the framework in-order to gain good insights.

5.2 Theoretical frameworks:

For studying the present scenario of a DC grid system for buildings in the Netherlands, a theoretical framework is necessary. There are two frameworks which support analyzing the market from different perspectives. One is the Multi-Level Perspective (MLP) approach and the other is the Function of Innovation System (FIS) approach. These two approaches are discussed below and checked for the fulfilment of the above-mentioned criteria. As an outcome of criteria fulfilment one framework among the above two will be used for analyzing the DC grid system in buildings.

5.2.1 Multi-Level Perspective

In this section, a brief description of Multi-Level Perspective (MLP) and its different levels will be discussed. The MLP approach is divided into three different levels: The Niche level; The Socio-Technical Regime and the Landscape which is also referred as micro, meso and macro levels, respectively [31].

The first level, the niche level (micro) is a protected market space for new upcoming innovations. This level allows learning processes for the innovation in the relevant fields in-order to increase the chance of survival in the current competitive regime.

The second level, the socio-technical regime (meso) is the current status quo. This level has a complex interaction between the actors involved in the particular technology and usually it is very stable and difficult to change. Actors such as companies, governments, universities and users are some examples that influence the current regime.

The third level, the landscape (macro) are external factors such as society, climate, lifestyle, culture or large economic trends etc. A change in this level are usually slow, but a quick change may also occur, such a change has a huge impact on rest of the two levels.

The above-mentioned three different levels of the MLP framework define the diffusion process of a technology into the market. Geels [32] explains that the diffusion process generally results from interaction between these three levels. The MLP has proven to be a usable tool for providing insight in the highly complex interaction between the actors associated with a certain technology. These interactions specify the significance of the three different levels and the market opportunities that will be present at different levels for the success of the technology. The Figure 5.1 shows an overview of the three levels and its operations.

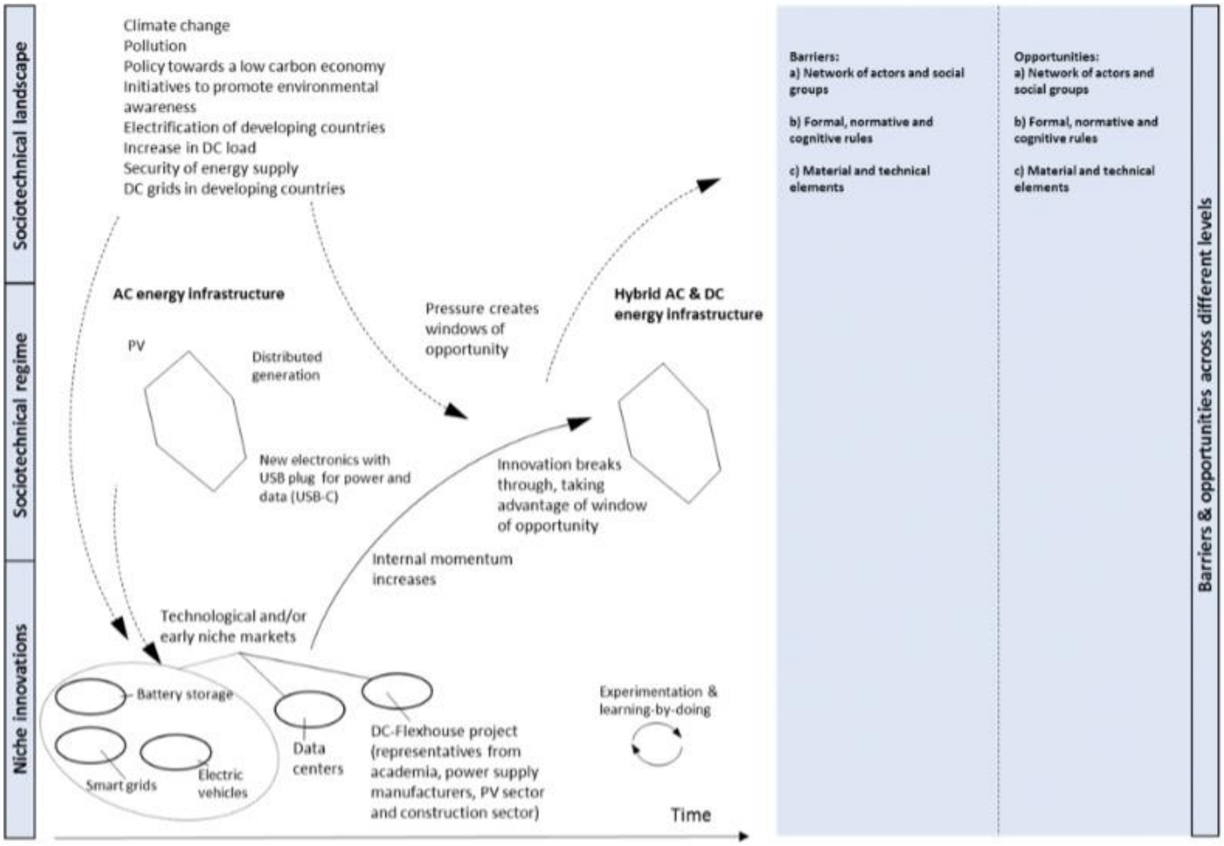


Figure 5.1: Multi-level Perspective [2]

5.2.2 Function of Innovation System

The Function of Innovation Systems approach (FIS) is an analytical framework used to determine if the technology can diffuse from niche to a wide spread market [33]. FIS is a system approach which consists of all the actors, institutions and regulations that influence the technological diffusion in a society. A key feature of this approach is that it not only concentrates on the individual contribution but also concentrates the collective contribution for the diffusion of the technology [34].

The FIS approach has been defined with seven functions/processes which should be analyzed in order to determine the potential of the technology. The result from this approach will give an overview whether the technology will or will not successfully diffuse into the market. It is not essential for the market to concentrate on all the seven functions, even fulfillment of an individual function will increase the change of technology being adopted in the market. This will be discussed in virtuous (positive) and vicious (negative) cycles. The seven functions of the FIS approach are listed below and its relevance for this research is explained in Table 5.1.

1. Entrepreneurial activities
2. Knowledge development
3. Knowledge diffusion through networks
4. Guidance of the search
5. Market information
6. Resources mobilization
7. Creation of legitimacy/counteract resistance to change.

Table 5.1: Seven function of FIS [35][34]

Function:	Indicators per function:
Function 1: ***Entrepreneurial activities***	In this function 1, the entrepreneurs responsible for DC grid systems in buildings, their sizes and their recent and future activities will be explored. This study of entrepreneurs will give an idea whether present stakeholders actively participate in the diffusion.
Function 2: ***Knowledge development***	In function 2, there are three learning mechanism for identifying the knowledge development: 1) Learning by searching – In this mechanism, the research and development (R&D) of DC grid systems, the amount of scientific research applied, and the available real-time projects will be explored. Along with this, the actors responsible for these real-time projects from the function 1 will be identified. 2) Learning by doing – From this mechanism, the cost of the new technologies or components and the experience from the real-time projects will be gathered. 3) Learning by using – Feedback is an essential key factor for the development. In this mechanism, the experience with the DC grid system will be explored for further analysis.

Function 3: ***Knowledge diffusion through networks***	Function 3 is used to explore the quality of knowledge transfer through networking. For combining the actors and stakeholders responsible for DC grid systems, networking will be achieved via conferences, seminars, joint projects, congress, formal or informal meetings etc. Such networking events and linkage congress responsible for DC grids will be identified.
Function 4: ***Guidance of the search***	It is vital to align the stakeholders in a specific path to achieve the vision and boost the opportunities for the technology diffusion. This vision and its corresponding rules and regulations for DC grid systems in buildings will be assessed using this function.
Function 5: ***Market formation***	The new technologies initially are not robust for competition with well-established technologies, in such a way it requires support for development. In function 5, the policies regarding tax exemptions, interest rates, subsidies for development of the DC grid systems in the Netherlands will be identified and discussed.
Function 6: ***Resources mobilization***	In this function, the resources required for development such as financial resources (incentives/subsidies), human resources (employees, education programs, researchers), material resources and its availability will be addressed.
Function 7: ***Creation of legitimacy/counteract resistance to change***	The opinion about the LVDC grid from the public or its users will be gathered and the hurdles for development will be analyzed. And in this function, the present LVAC grid regime's support for the development of LVDC grid system will be identified.

Function 1-7: ***Dynamics between the functions***	Virtuous and vicious feedback cycles between the functions give a clear view of positive and negative effects caused on each-other. This shows the present situation of DC grid systems for buildings in the Netherlands from the study of seven FIS functions.

From the Table 5.2, the green ticks show the criteria satisfied by the framework. The MLP approach does not support the criteria dynamic analysis and comparison between the systems. The MLP gives a comprehensive overview of the change and provides a broad perspective of the interconnection between the actor and the stakeholders responsible for the diffusion of a technology. The focus of MLP is more towards the social learning which is considerable for large scale social transitions when the technology is already in the market. However, in the case for LVDC grid system inside buildings, a huge social transition has not taken place so far.

Table 5.2: Criteria for selecting the framework [30]

	Framework	**FIS**	**MLP**
Criteria	Technology specific	✓	✓
	Dynamic analysis	✓	✗
	Infrastructure	✓	✓
	Allow for comparison between systems	✓	✗
	Linkage between the actors and stake holders	✓	✓
	Wide analysis	✓	✓

The research is carried out to identify a possible scenario for LVDC grids for buildings in the Netherlands. For which a widespread understanding from both technical and business perspectives is mandatory. The FIS framework provides seven functions which focuses on technological as well as social aspects. The FIS approach is comprehensive, holds a specific area and provides comparison for different technologies. For these reasons, the main research framework opted for this research is the Function of Innovation System (FIS) approach. In order to collect the data required for this research, desk research and interviews are performed for the FIS functions which will be discussed. The following section will discuss the technology map of the LVDC grid.

5.3 LVDC grid in buildings – Technology map

In this section, an empirical study of the LVDC grid for buildings is discussed with respect to DC generation, DC storage and DC load technologies and categorized in a technology map.

5.3.1 DC sustainable energy sources:

The key purpose for changing to a DC grid inside buildings is due to Distributed electricity Generation (DG). This generation is achieved using sustainable electricity sources such as photovoltaic (PV) and fuel cells (FC). In principle, both the sources generate DC and PV uses daylight as a source and can be easily installed on roof tops and side walls (BIPV) of the buildings. The BIPV is known as building integrated PV and similar to BIPV, now-a-days windowpanes are also coated with a chemical composition for DC electricity generation [36]. Moreover, the fuel cell (FC) technology is a fast-growing concept in the field of transportation supporting electric vehicles (EV). This FC technology may be incorporated as a generation source for buildings using a Vehicle to Grid (V2G) concept in the near future [37]. Likewise, the huge on-shore and off-shore wind turbines are also connected to the present main AC utility grid using a DC link. This is because the AC electricity generation by a wind turbine cause difficulties in controlling the AC frequency and voltage according to the utility grid standards [38].

5.3.2 DC Storage:

The sustainable energy sources rely on the nature of sunshine and wind flow, these natural sources for electricity generation are intermittent. So, the usage of decentralized electricity generation is only possible upon availability of the sources. In-order to overcome this situation, the storage technologies are incorporated with DC grid systems to make it more reliable. An utmost advantage of storage is that the storage components purely store DC. The electrical energy storage technologies are batteries and ultra-capacitors. Even flywheels are also used along with the wind turbines which can store mechanical energy for short period of time (minutes) and can support rotating the turbines for generating electricity. Also, the surplus generation of DC source can be used for the generation of hydrogen using the principle of electrolysis and hydrogen (H_2) can be stored in tanks of cars. This stored hydrogen can later be used for transportation and vehicle to grid (V2G) using Fuel Cell (FC) technology [38].

5.3.3 DC loads:

The quantity of DC loads is constantly increasing due to solid-state electronics used in appliances such as laptops, mobiles, computers, printers, televisions, VFDs and many more, making DC grid systems even more inevitable. But, in the present-day regime, the electronic devices internally run in DC, but are supplied with AC using an AC/DC converter.

Along with the other technologies, connection technologies are mainly used to connect generation sources, storage and loads. These are MPPTs for PVs, DC/DC converters for loads, DC/DC LED drivers for lighting and Pulse Width Modulator converters for variable speed motors. In the technical potential of this thesis, the loads such as laptops and mobile phones are used in DC supply using readily available DC wall socket (Figure 2.3). Along with these, the other DC loads discussed above are also readily available at the niche level which can operate using DC supply. The main hinderance for the breakthrough of these products into the market were standardization of the DC Voltages. But recently the rules related to DC voltages are implemented by Dutch Practical Guidelines (NPR) which will be discussed in function 4 of the FIS.

5.3.4 Electric Vehicles (EVs) and Fuel Cell Electric Vehicles (FCEVs) as DC generation and DC load:

In the European region, a substantial part of the air pollution is caused by usage of fossil fuels for road transportation. An average car emits 4.7 tons of CO_2 per year [14]. So as to mitigate this emission of CO_2, the Dutch government along with the support of social and economic council are introducing steps for banning Internal Combustion (IC) engines by 2030 [39].
Not only in the Netherlands, but also in countries around the world EVs and hybrid EVs are already on roads. For making transportation sector cleaner and sustainable, the FCEVs also play a vital role in achieving the goals of sustainable transportation. The FCEVs use hydrogen (H_2) as fuel and the DC electricity generated from a FC is used for rotating the electric motor connected to the drive train.

The EVs and FCEVs act both as generation sources and loads. The concept of the project Car as a Power Plant (CaPP) is to connect FCEVs and EVs to the grid. It is analyzed that a car is used only 5% of its time for transportation and the rest of the time it is parked [40]. During the parked timing, the car acts as a generation source and provide DC electricity to the building or vice versa. Thus, increasing the need for a DC grid system.

5.3.5 Technology map of DC grid system for buildings:

In this research, the architecture of a DC grid system and its optimization of storage and generation will not be discussed as this is considered outside the scope of this thesis. Further knowledge about DC grids it can be found in [17]. All the above-discussed technologies are assembled into an overview leading to a technology map as shown in Figure 5.2. The DC grid system inside a building is a combination of generation, storage and loads, the arrows in the map represents the in-flow and outflow of the DC electricity.
In addition, the DC grid system has the capability for local control and can disconnect itself from the main grid which is known as islanding mode. The DC system as a whole has a better efficiency when DC loads are combined with DC generation and storage [25][38].

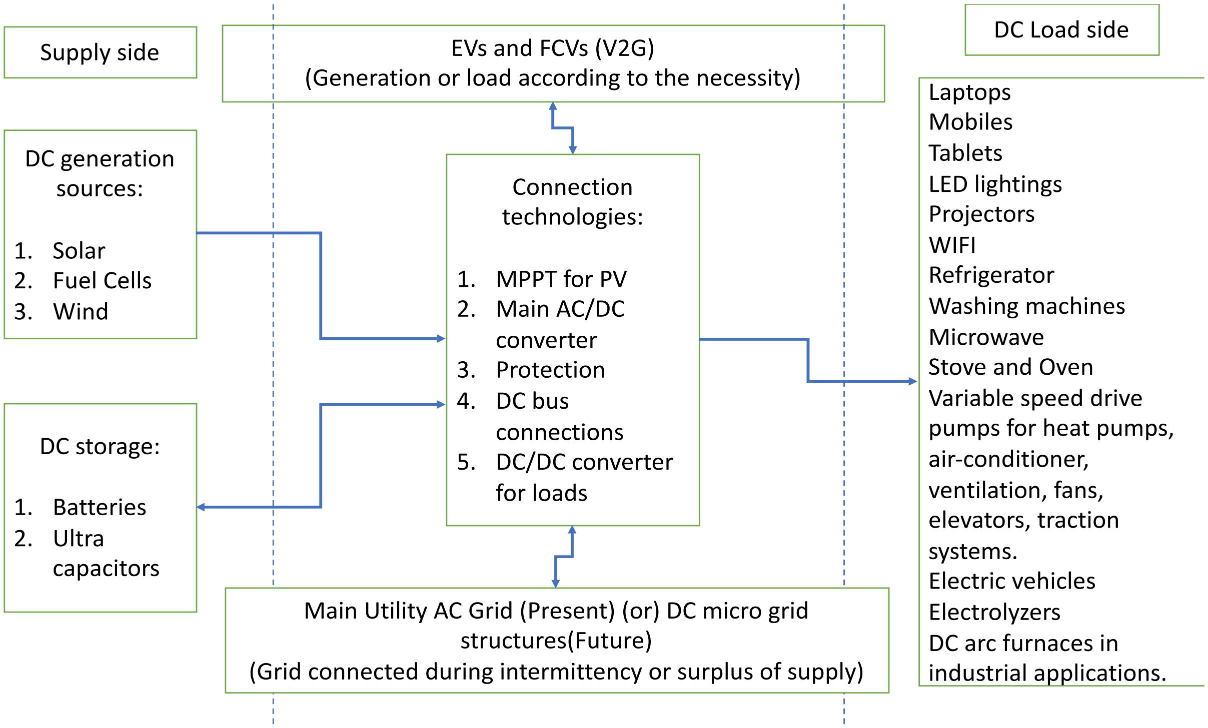


Figure 5.2: Technology map of a DC grid system

A significant setback for the DC grid systems inside buildings is the DC bus connection. In the existing AC grid systems, the AC bus connections for buildings are well structured as either single-phase connections or three-phase connections according to the well-established regulations (NEN1010) and standards. For the DC bus connections, the regulations and standards are being developed through knowledge sharing from various pilot projects in the Netherlands discussed in the seven FIS functions of the upcoming section.

5.4 FIS analysis for DC grid system for building in the Netherlands:

In the present energy landscape, the AC grids are based on central power generation and high voltage AC transmission lines in-order to supply the loads. From this point of view, the electricity flows in one direction. Now, the renewable electricity generation has changed this flow bi-directionally, increasing the opportunities for Distributed Generation (DG). The government and its polices related to mitigation of climate change is favorable to DG, but the present energy infrastructure is quite inefficient and sometimes old hindering diffusion of new technologies into the market. So, many research organizations, institutions and Multi-National Companies started research in revamping the energy infrastructure into DC grids both inside and outside buildings. The DC grid system inside buildings depends on different technologies as shown in the technological map above. In this chapter using seven FIS functions, the organizations, companies, research institutes, pilot projects, rules and regulation and policies related to the current market scenario of DC grid systems for building in the Netherlands are explored and finally DC grid system barriers and drivers are discussed.

Table 5.3 below shows the indicators that will be used within and between seven FIS functions for market analysis.

Table 5.3: Indicators

Function:	Indicator per function
Function 1: Entrepreneurial activities	Which entrepreneurs are in action regarding DC grids?
	What are their recent activities?
Function 2: Knowledge development	What are the projects on-going related to DC grids in buildings? Who are all responsible for the projects and researches? What is the feedback from the project results?
Function 3: Knowledge diffusion through networks	What are all the means of knowledge transfer among different actors/stakeholders?
Function 4: Guidance of the search	What are the goals set by the government to support DC grid systems for buildings? What are the rules and regulations set by the government?
Function 5: Market formation	Are there any direct subsidies or stimulation programs for supporting DC? Who are all the foreseen potential customers for DC grid systems in buildings?
Function 6: Resources mobilization	Financial resources Human resources
Function 7: Creation of legitimacy/counteract resistance to change	The public acceptance of technology. Is there any resistance from existing dominant regime?

5.4.1 Function 1: Entrepreneurial activities

The DC grid system inside a building is a combination of different technologies. The present-day installation of DC generation sources is recognized world-wide and there are several entrepreneurs involved in it. But the connection technologies for DC inside buildings are not well-established. For this function, the Table 5.4 discusses the entrepreneurial activities for connection technologies, new DC loads and innovative DC generation & storage related to DC grid systems in the Netherlands.

Table 5.4: Entrepreneurial activities in the Netherlands

Entrepreneurs	**Activity**
Direct Current:	Direct Current BV is a young and innovative company with a great vision on DC technology. They are specialized in power electronics and manufacture DC components for industries, commercial buildings, offices, street lightings along with the sister companies DC Systems BV, Hellas Rectifiers BV, Femtogrid Energy Solutions BV and Amstel Rectifiers BV. They manufacture AC/DC current routers, DC/DC converters, cathodic protection, battery chargers, combiner boxes for solar installation etc. Direct Current is also responsible for several pilot projects with DC grids in buildings discussed in function 2. [41]
DC Opportunities:	DC Opportunities share knowledge and expertise in low voltage DC and are actively involved in the research for DC grids systems. They do research in DC protection, grounding, Islanding, bi-directional flow DC/DC converters, USB – C power delivery and demand response. They also have developed some products among these, and it is yet to be licensed. [42]
CITYTEC:	CityTec is a company highly experienced in advice, management and maintenance for public lighting in government and public buildings. They also take responsibilities for 500,000 lightpoles, 30,000 traffic lights and 2000 parking spaces all over the Netherlands. CityTec has installed DC public lightings in various locations of Netherlands in collaboration with provinces and municipalities. CityTec is currently running many pilot projects for DCLED street lighting using combi cables which have provision to transfer both AC and DC. These cables can be used for buildings in near future.[43]
victron energy:	Victron energy is a R&D company which designs and sells inverters, charge controllers and power conversion products. These products are sold worldwide in off-grid solar, industrial, automotive and marine markets. Victron is a major supplier for devices in the 48V_{dc} setup of the DC Office. [44]

ABB:	ABB is a global leader of power grids, electrification products and automation serving for commercial spaces, industries, transport and infrastructure world-wide. They are involved in various high voltage DC grid projects around the globe and pioneers in developing electrification products. In Netherlands, they are involved in collaboration with various companies in several projects for a DC grid system in buildings. [45]
SIEMENS:	SIEMENS is an expert in various industries of energy, automation, transportation etc., including all these, it is also mastering the challenges of changing energy systems. It provides solutions for decarbonization and distributed generation using HVDC transmission solutions over long distances. At present, it is working on projects of onshore and offshore grid connections. In near future, Siemens will be a potential partner in providing LVDC transmission solutions for buildings and distribution networks. [46]
ReXeL:	ReXeL Nederland BV is a part of ReXeL group world-wide and is a leading distributor of electrical materials. They provide products and solutions for cost-effective sustainable solutions. They are currently involved in DC grid projects for buildings and a stakeholder in executing the DC Office project. [47]
eNGie:	eNGie is an energy company and technical service provider focusing on sustainable development, energy efficient smart buildings and clean energy. In Netherlands, they are responsible for technical support in several DC grid systems projects for buildings.[48]
GTV:	GTV is an installation and prefabrication company which provides complete solutions in electrical engineering. GTV is currently providing services for DC pilot projects and it also has installed panels, distribution boards and assembled converters for $48V_{dc}$ in the DC Office project.[49]
Other connection providers:	STEDIN (Joulz – part of STEDIN), Alliander and Enexis, are the leading distribution system operators in Netherlands and they are involved in collaboration pilot projects such as DC Combi cables and DC homes. They are also upcoming with new concepts of a flexible energy market and demand management for DC grid systems which includes sustainable energy sources, V2G, batteries storage in homes and Internet of Things.[50][51]
Other entrepreneurs in generation, storage and loads:	

PHYSEE:	PHYSEE is a startup company for façade technologies that generate electricity. These power windows can be installed in residential or commercial buildings to generate clean electricity. There are many pilot projects of PHYSEE that are ongoing in the Netherlands. [52]
KITePOWER:	KITePOWER is a startup company with an innovative idea of generating electricity using wind and kite in remote locations.[53]
AquaBattery:	AquaBattery is a flow battery company, it manufactures electrical storage system which is using water and table salt. The product BlueBattery will be a great solution for sustainable electrical storage.[54]
Electric Vehicles:	EVs are now manufactured by most of the leading automobile companies. Some of the existing EVs in Netherlands market are Tesla, Volvo V60, Opel Ampera, Audi e-tron, Nissan Leaf, BMW i3, Volkswagen e-Up! Chevrolet Volt, and many more. The usage of EVs in Netherlands are increasing according to the report of electric vehicles by RVO (Rijksdienst voor Ondernemend) [55]. EV car manufacturer Tesla also patented a new battery technology with better longevity, fast charge and low-cost battery which will enhance even higher diffusion of EVs into the market. [56]
Fuel Cell Electric vehicles:	Fuel Cell Electric Vehicles (FCEVs) are not as well established as EVs world-wide. But in Netherlands various projects using FCs are being implemented in public transport buses and 17 new public hydrogen fueling stations will be installed by 2020 [57]. Globally there are only outnumbered FC cars such as Toyota Mirai, Hyundai Nexo, Honda FCX Clarity, Hyundai ix35. Building hydrogen fuel stations will be a real breakthrough for the hydrogen economy and FCEVs in Netherlands.
New DC loads:	Most of the loads at present cannot be directly operated in DC, but the manufacturers are ready with prototypes for some of the devices for operating in DC directly. Some of the companies ready with prototype are: NRGTEQ heat pumps, ETHERMA infrared heaters, ESYLUX intelligent lightings, Philips LEDs etc [58][59][60][13]. The laptop and mobile phone companies are also providing with USB – C type chargers for standardization of laptop ports and chargers. The companies that adopted to USB -C in its new devices are Apple, DELL, HP, Samsung, Microsoft, OnePlus etc. [61]

From the function 1, it can be understood that there are many entrepreneurs working on the change towards DC grid systems for buildings. With different business models and interest of each and every stakeholder they differ from each other to develop DC grid systems. The following function 2 shows the pilot projects related to the DC grid systems in buildings.

5.4.2 Function 2: Knowledge development

In this function, the current status of DC grid systems in buildings are gathered according to learning by searching, learning by doing and learning by using mechanisms. The present on-going projects related to the DC grid systems in buildings and responsible institutes are identified.

5.4.2.1 Learning by searching:

The potential of DC grid systems in near future can be identified from the amount of scientific papers and research published over a time. According to [62], number of researches published related to DC smart grids are exponentially increasing worldwide. From the year 2012 to 2015, more than 4000 publications were released per year. From 2016 till November 2018, the researches published increased to 5600 publications per year globally. Among which, Europe holds 37.5%, USA holds 22%, China holds 19% and other countries hold 21% as share of publications. In EU according to Joint Research Centre of European Commission's report, 953 smart grid projects have been funded since 2007 by 2900 different organizations.

Among various research institutes in Europe, ECN and TNO in the Netherlands are actively involved in various energy transition researches for achieving zero carbon emissions by 2050. In which some of the research projects TNO currently working are related to future proof of energy systems, DC/DC converters, electric mobility and legislation & regulations for speeding the technological developments.
ECN is an Energy Research Center of the Netherlands where several projects related to solar, wind, biomass, storage and its integration researches are in process. In particular related to the DC grid infrastructure, both ECN and TNO are working together in '*reliable sustainable energy system*' project which works on energy conversion and energy transport infrastructure.

5.4.2.2 Learning by doing:

After research, the second step for diffusion of new technology into the market requires a strong development. For which, the companies collaborate with educational institutes like TU Delft, TU Eindhoven, Haagse Hogeschool, Zuyd Hogeschool for knowledge and skills for developing the DC grid systems for buildings. The entrepreneurs discussed in function 1 are involved in one or more projects for development of DC grid systems in buildings. Some of their on-going pilot projects in Netherlands are shown in Table 5.5.

Table 5.5: LVDC grid in buildings - Pilot projects

Pilot Project in NL	Partners	Type
DC Office	Rexel Nederland, Engie, Victron Energy, FLUKE, Jowitherm, Philips, Direct Current, GTV, TU Delft, The Green Village.	Commercial building
ABN AMRO CIRCL pavilion	BAM, Engie, Direct Current, ABN AMRO.	Commercial building
AFAS theatre Leusden	Direct Current	Commercial building
Johan Cruijff ArenA	Eaton, Direct Current	Commercial building
Lelystad Airport Business Park	OMALA, Liander	Commercial building
PULSE building	Direct Current, TU Delft, RHK.	Educational building
DC Connected Homes	Alliander, TU Delft, The Green Village.	Residential building
DC FLEXHOUSE	IBC Solar, Zuyd Hogeschool, Haagse Hogeschool, ABB, Direct Current, Siemens, Wijk van Morgen	Residential building
DC = DeCent	Siemens, Kema, Joulz, DC Foundation, SGN.	Horticulture glass building

From chapter 3, the LVDC grid for small buildings is shown to be energy efficient compared with the LVAC grid. From chapter 4, the LVDC grid in small new buildings is cost efficient compared with LVDC grids in small old buildings. For the LVDC grid in big buildings such as ABN AMRO Circl, AFAS theatre, Johan Cruijff Arena, PULSE buildings, the results have to obtained and further researched to explore the potential.

5.4.2.3 *Learning by using*

Learning by using is a feedback from users to producers, as DC grid systems for buildings currently concerns a niche market and there are only few pilot projects on-going in real time. From which the ABN AMRO CIRCL pavilion project revealed an article stating that "the large installation companies are now convinced about the advantages of DC and they see DC as an opportunity." [63]. Also, in the above-mentioned project, the building was operated in island mode for few hours without a battery system and it is shown that the DC system can maintain and balance between production and demand.

5.4.3 Function 3: Knowledge diffusion through networks

As discussed in function 1 and function 2, there are several stakeholders involved in DC grid systems for buildings and play a vital role in the development of the technology. For all these stakeholders, there should be a proper knowledge diffusion in-order to move forward in the same direction. This knowledge diffusion is transferred through publications, conferences, technical seminars, test beds, media etc. In Netherlands, the communication between the stakeholders is really extensive which contributes to the development of DC technology. For the development of DC in the Netherlands a DC foundation named “Stichting Gelijkspanning Nederland” has been formed. Here DC conferences have been conducted in the year 2018 and one more will be in the year April 2019. In this DC Congress, stakeholders present their ideas, progress and views on DC grids altogether.

Also, through educational and research institutions, the DC grid is ensured by joint work with new standards [64] in the test bed facilities like The Green Village (TU Delft), Wijk van Morgen (Eindhoven) and EnTranCe (Groningen). Meanwhile, the media like BNR Dutch news radio telecasts the show “The Green Quest” every Monday at 3 pm in-order to diffuse knowledge about ongoing sustainable projects [65]. There are also online media journals for the Netherlands like “DUURZAAM Bedrijfsleven.nl “and “installatiejournaal.nl” for updates on sustainability projects. [63] [66]
From the evidence of knowledge diffusion, “the pace in which the Netherlands move to achieve 2020 climate target is very slow and the Dutch business community has to work hard” [65]. In an interview of Harry Stokman in DC Foundation, he said that *“this has to involve people who think on a system-level and not in small boxes. Each stakeholder has its own interests and thinks only of what benefits them. To integrate the system as a whole, this has to change and a broader, helicopter vision needs to be followed”.* By this vision, TenneT and Rexel are already in discussion about installing a DC grid system along with the guidance discussed in function 4.

Apart from this, my own experience as a DC grid user in office setup, it is more user-friendly than AC in a building environment. One would agree that it would be easy not to carry a converter for laptops and mobiles where ever they go (Just the USB – C cable is enough to supply DC power for laptop and mobile phones). Initially, the protection systems for LVDC grid was a disadvantage because it was not fully developed [2]. But now the protection for LVDC is achievable by 350 V_{dc} current routers designed by Direct Current BV which is used in the DC Office setup. Furthermore, when DC expert Harry Stokman (CEO, Direct Current BV) was interviewed, he said that usage of AC electricity in commercial buildings will be an option for customers in near future. (Refer to Appendix C)

5.4.4 Function 4: Guidance of the search

The guidelines for DC grid systems in the Netherlands are supported by both EU programs and the Dutch government. At EU level, there are several programs to stimulate the technical innovation for mitigating climate change. Some of the EU programs are Horizon 2020 and Interreg. The Horizon 2020 is a subsidy tender which covers research and development of all topics of sustainability projects inside EU and Interreg aims at connecting with cross-borders. In the EU, all High Voltage, Medium Voltage and Low Voltage DC levels are discussed. In this thesis, only LVDC is taken into consideration. For which, the round table discussions in EU level debates about the standardization of LVDC voltage levels, wiring systems, protections, metering and installations. For the standardization of the voltages it is discussed to be <325V_{dc}. It also came up with decision [67] that research, development & innovation of DC powered homes, commercial buildings with smart grids should be demonstrated as a real-time project. Some guidance for such projects from EU level discussions are as follows:

1. These projects should be with EV, storage and PV aiming at increased self-consumption.
2. The projects will be a good platform for bodies to collaborate like electric utilities, manufacturers and end users.
3. Possibility of evaluation of "*DC ready*" label should be used in devices which will rapidly increase the diffusion of DC culture and more devices will be accepted by the users, ultimately improving the diffusion of DC grid system [67].

In Netherlands the government programs guide by setting goals to be achieved in buildings before 2050. From "Rijksvastgoedbedrijf" ministry of real estate agency, it has announced that real estates in Netherlands have to be energy-neutral by the end of 2050 [68]. The step by step goals for guiding the vision are as follows:

Step 1: From 2019, new government buildings have to be virtually zero energy buildings by including energy efficient lightings, climate control, Internet of Things (IoT).

Step 2: From 2020, 14% of total energy consumption should be from renewable energy.

Step 3: From 2023, 16% of energy from renewables and all the office buildings should be with energy label C and government buildings with energy label B.

Step 4: From 2030, 50% less usage of primary raw materials.

Step 5: From 2050, the energy supply is fully sustainable and CO_2 emissions is zero.

From all these steps, it shows a clear vision for the diffusion of DC grid systems into the market. For this in the Netherlands the "Bouwbesluit" i.e. building code, makes sure that all the devices are designed and operated in safe way. For which, there are several rules and regulations. The most common in the Netherlands is NEN1010. The NEN1010 is a safety and regulations code for LV installations (Veiligheidsbepalingen) and it describes for all LVAC 50 V_{ac} to 1000V_{ac} installations. Along with this description, it also adds a statement that "every AC term can also be read as the equivalent DC term [41][69]. From which, the first DC installations rules are framed in Netherlands by Dutch Practical Guideline NPR 9090 for new standard LVDC installations, core colors for cables and many other DC installation cases. This was issued on April, 2018 by NEN and implemented on November, 2018 [70]. This NPR 9090 is a guideline of installers that will work with DC. These guidelines state that the knowledge and skills described in the NPR should be transferred to electricians and electrical engineers who are not dealing with DC on daily basis.

5.4.5 Function 5: Market formation

The installation of DC grid systems in buildings has now entered into a new phase concerning standardization. In this phase, the government needs to come up with new policies and subsidiary schemes particularly for DC grids in buildings. Already, in the Netherlands, SDE (Stimulering Duurzame Energieproductie) is a subsidy policy by the Ministry of Economic affairs and climate policy (RVO – Rijksdienst voor Ondernemend Nederland) [71]. This policy encourages people for production of renewable energy in all sectors. Apart from this, the popular support policies are investment policies, tax exemptions, low interest loans, feed in tariffs and R&D grants provided by RVO and the Horizon 2020 EU subsidy program. These policies support for DC generation. Also, for EVs the government has decided to achieve 200,000 EVs before 2020 [72][73] by providing subsidies. These subsidies for DC generation and EVs in-turn help for DC grid systems to develop in one way or another in near future by V2G concepts. But there should also be direct policies supporting DC grid systems, for which the Joint Research Center of the European Commission has allocated €5 billion for the development of DC smart grid projects [62].

From function 1 and function 2, it can be seen that there are interesting group of companies, organizations and institutions involved in DC projects. The government should help these stakeholders with supportive policies for market formation in near future. A detailed policy map for DC grids in buildings along with policy instruments can be found in [74]. Also, Figure 5.3 below from research [2] shows the penetration of DC grid systems into the market. The innovators (2.5%) have already started to implement DC grids for buildings in the Netherlands. Similarly, while interacting with Harry Stokman, he also added that he sees commercial buildings as a potential market for DC grid systems to diffuse and later followed by agricultural and residential sectors.

All the gemeente (municipalities) in the Netherlands are working on implementing new sustainable policies and solutions for promoting sustainability. Among which, the Amsterdam gemeente is coming up with the policies to achieve the sustainable city project by 2040 [75]. For which, it has decided to make the homes, businesses, sport clubs, schools and community organisations sustainable and more energy efficient. Some of the initial phase demand side customers for DC grids are football stadiums (sport clubs – Amsterdam Arena) have planned to change a part of its system to DC grid along with DC generation and storage. Also, a potential demand for DC grids are foreseen in large commercial buildings with innovative image (ABN AMRO CIRCL), newly built commercial buildings, educational buildings (schools, universities, libraries), public bus service station and EV charging points[76].

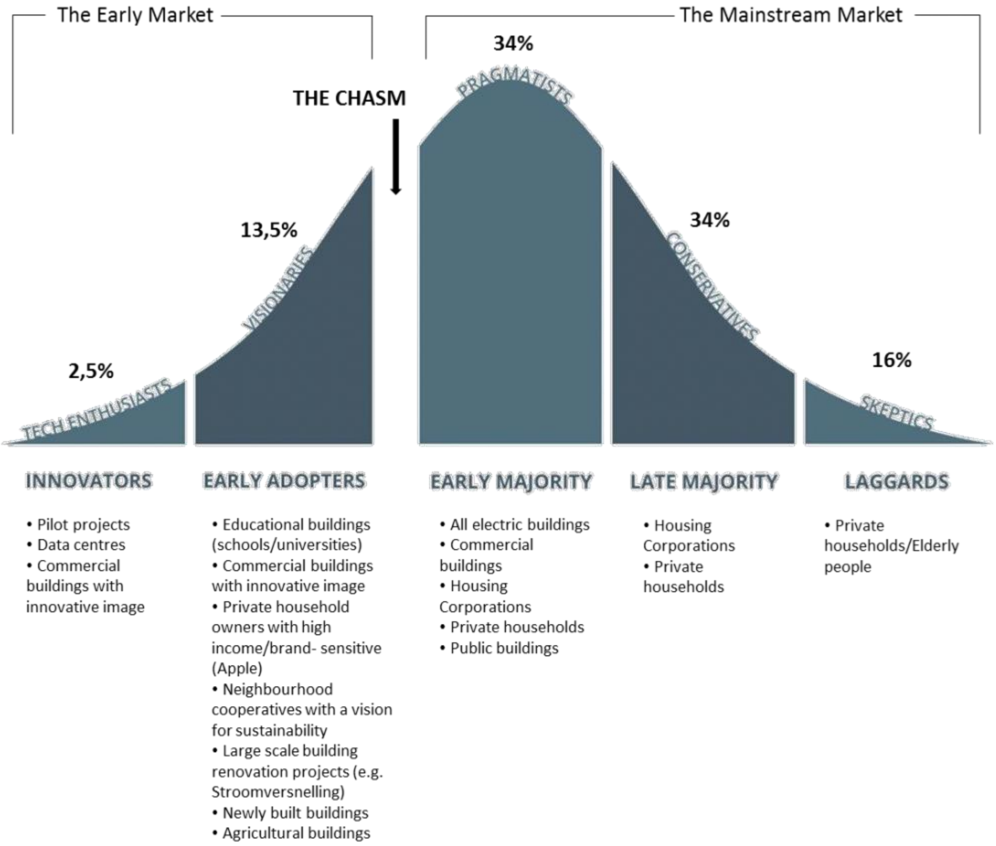


Figure 5.3: LVDC grid in buildings - Market formation[2]

5.4.6 Function 6: Resource mobilization

In function 5, the Dutch government and EU subsidies related to DC grid systems were discussed briefly. From the discussion, it can be identified that the financial resources are available for development, but currently there are no vivid and robust policies for supporting DC grid systems, particularly concerning incentives. So, the financial resource mobilization is low from a subsidy perspective. But the regime manufactures such as ABB, Siemens and energy distributors like STEDIN, Alliander and installers like BAM, eNGie, Eaton and material distributor Rexel invested their money for research and development of DC grid systems in real-time projects realizing the potential of a DC future (refer Table 5.5).

For human resource mobilization, the standardization of practical guidelines for DC grid systems has been taken up recently. This implementation of guidelines for DC grid systems will improve job opportunities in near future. The technicians, engineers and other installers have to be educated with respect to the DC installations and certificates have to be issued [70].

5.4.7 Function 7: Creation of legitimacy/Counteract resistance to change

From exploring function 2 and function 5, the DC grid systems for buildings in the Netherlands are implemented in few real time places as shown in Table 5.5. The validation of these existing real-time projects with DC grids are yet to be revealed. Meanwhile, from the ABN AMRO CIRCL Pavilion project, it has been proved that the DC grid system is efficient compared to an AC grid system with respect to low energy consumption, less material consumption from AC transformer materials and copper savings for big buildings. In addition to this during a field visit to the ABN CIRCL, an installer from Direct Current BV explained that the present TVs and projectors in the building are connected using DC/AC inverters and these can be also replaced in all the devices by its manufacturers in near future as these products become available for DC supply.

Likewise, from the Psychology department of Leiden university, an interesting thesis “the acceptance of DC electricity in Dutch households” [77] came up with an interesting conclusion of a positive attitude by people towards DC houses. From their findings, the people have high intensions to purchase DC houses. This positive attitude shows an acceptance of DC grids in near future by the residential sector together with a vision for 2050 in function 4. Beyond all the above, the most important factor for penetration of DC into the market is subsidies. Some of the previous subsidies provided by Dutch government for Renewable Energy Development (RED) shows that the Netherlands have been showing progress in wind and solar DC electricity generation than the EU’s average [78]. Similarly, the policies for DC grid systems shall be implemented by the Dutch government to check the penetration of these systems into the market.

As discussed in function 1, the DC grid systems have potential actors and stakeholders for performing the paradigm shift. Only a few real-time projects are implemented in the Netherlands so far, and the results are yet to be obtained (except the ABN CIRCL project). It is hard to analyze the resistance of such DC grid systems without proper results. There are multiple stakeholders involved of various types such as policy makers (NEN/NPR), Regulators (Dutch government/EU), Manufacturers (ABB/Siemens/Direct Current), Installers (GTV/ eNGie/ Direct Current), Consortia (DC Foundation) and Distributors (Materials – Rexel, Electricity – STEDIN/Alliander). A proper stakeholder analysis has to be performed as an extensive and detailed research in order to analyze the interests and motivation of all the above groups. From the activities of regime level AC electricity distributors like STEDIN and Alliander, their interest in DC grids is rising. It is also stated that in near future, the customers have to pay for usage of the grid infrastructure instead of the electricity [50][51].

5.5 Barriers and drivers for DC Grids in buildings:

According to the findings from the seven FIS functions, the barriers and drivers of DC grid systems are discussed in this section.

Barriers for development of DC grid system in buildings:

1) The existing devices in buildings use AC for lighting, PCs, televisions, laptops and other devices. So, the manufacturers design and sell DC products that is compatible and operates only in AC. Moreover, there is no provision for connection of DC devices in public/private buildings irrespective of the sector.

2) There are no government subsidiary policies particularly for DC grid systems in buildings to assist penetration into the market.

3) The rules and regulations for DC installations have been implemented recently and the technicians and engineers have to be trained and certified for DC.

4) The knowledge and awareness of DC grid systems for the public is not well-established.

Drivers for development of DC grid system in buildings:

1) Technically DC grid systems have more advantages than AC grid systems inside buildings. A DC system increases the overall efficiency, reduces the material usage and capital cost, increases sustainability & comfort and congestion management.

2) The rules and regulations for DC installations NPR9090 has been successfully implemented as practical guidelines by the Dutch government.

3) The new devices that can operate directly with DC supply are developed as mentioned in function 1. Also, the EVs usage in the Netherlands and H_2 fuel stations for FCEVs are increasing which in-turn will support the development for DC grid systems in the near future.

4) The guidance for the development of DC grids in buildings is clearly explained by Dutch government roadmap 2050. Also, the current AC regime supports for a DC grid structure, by focusing on researches like V2G concept, storage for homes, flexibility grids &market, supply management and financial incentives.

5) From the survey research of [77], people feel positive regarding DC houses.

5.6 Virtuous and vicious cycles:

The DC grid systems for buildings has several positive and negative feedback cycles between the seven functions. Figure 5.4 represents the interactions of the feedback cycles and are explained and argued in this section. The entrepreneurial activities by the actors discussed in function 1 have a positive impact on the market formation. This positive influence is due to the specific researches, real time projects and realization of DC in sport clubs across the country (Function 2 and Function 5).

The function 2 is the knowledge development, this function has positive effect on the knowledge diffusion (function 3). This is acquired from the learning by using part of function 2, which gives potential feedback from the LVDC grid users to the entrepreneurs working on several other projects (function 1). The potential feedback to the entrepreneurs will in-turn improve the design of the technology.

The market formation has a positive feedback into the guidance of search. This loop has stimulated the government to formulate the new rules and regulations for DC installations NPR 9090. Moreover, market influence along with the clear guidelines of 2050 stimulates the government to come up with policies for supporting zero energy buildings. For example: Amsterdam gemeente is implementing policies (grants and low interest loans) for shifting to electricity cooking and roof top solar panels. (Developing DC solar generation will in turn help for the LVDC grids market in the near future). The function 6 is resource mobilization which have two negative effects. The one effect is on the market formation specifically in terms of financial policies related to LVDC. There are several policies for development of DG generation and EV mobility, but scarce policies specifically related to LVDC grids. Likewise, the human resources (engineers, technicians, electricians) with LVDC knowledge is also scare for counteracting the resistance to change. The last function, creation of legitimacy has one positive effect on the market formation. The survey results from the Leiden university regarding acceptance of DC in houses is a positive sign for the development of the market. Although there is a positive social acceptance, there are very less steps taken for speeding up the LVDC grid in the buildings. The entrepreneurs and actors responsible for DC grids should enforce Dutch government and the municipalities for new policies and incentives specific for LVDC grids.

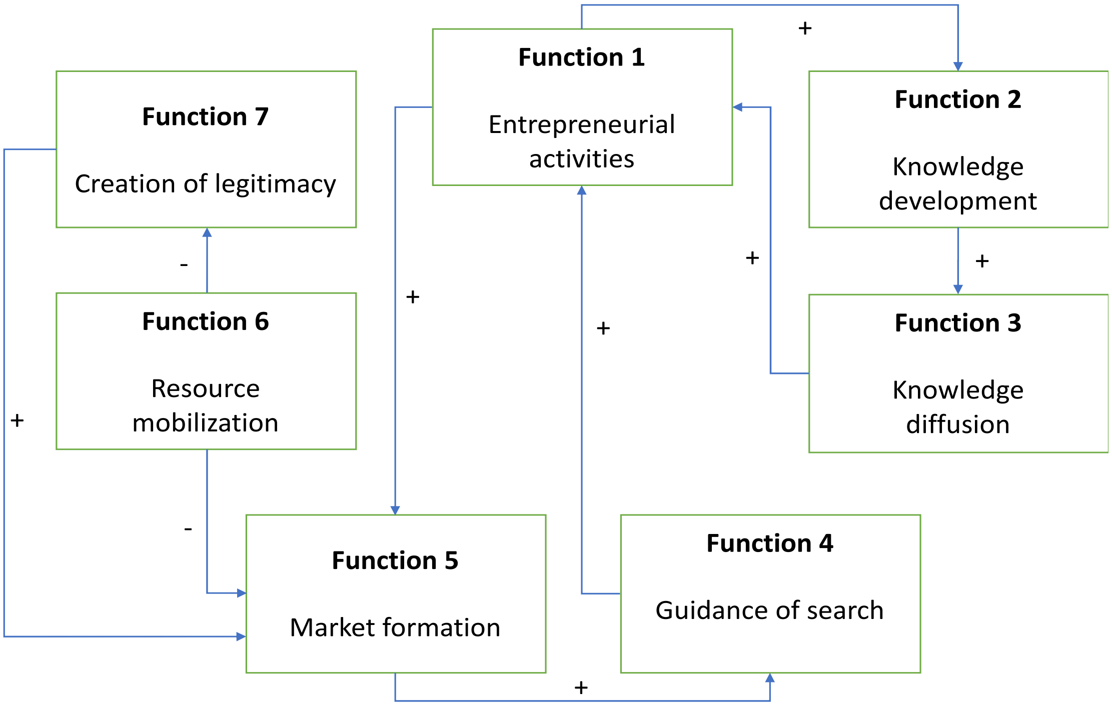


Figure 5.4: Virtuous (+) and vicious (-) cycles of LVDC grid for buildings in the Netherlands

6 CONCLUSIONS and RECOMMENDATIONS

The aim of this research is to find the technical potential and commercial potential of the LVDC grid from the 350V$_{dc}$ DC Office setup. For which, a literature review was performed on experimental LVDC grids and commercial potentials previously conducted across the globe.

Figure 6.1 is the flow of thesis that was followed:

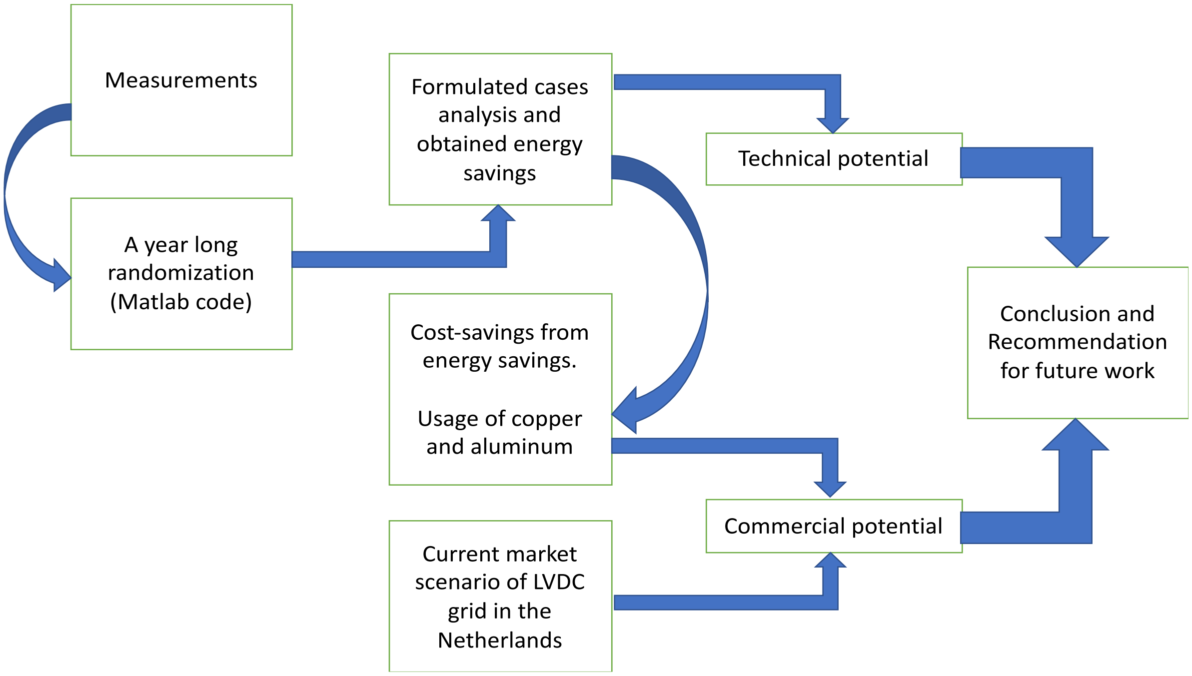


Figure 6.1: The flow of thesis followed

From chapter 2, results of the loads measured in LVDC and LVAC grids was discussed. For LVAC grids, 4-tubelights, 2 laptops & 1-Mobile phone and for LVDC grids, 2-LEDs, 2 laptops & 1-Mobile phone were measured. Using these measured results, in chapter 3 a year-long profile was randomized. For which, it was considered that office premises function from 8:00 am to 6:00 pm, using 32-tubelights, 10-laptops & 2-mobile phones in LVAC and using 16-LEDs, 10-laptops & 2-mobile phones in LVDC from the observation of real time office. For the randomization methodology, it is considered that tubelights and LEDs are turned-ON throughout the working hours and for variable loads (laptops and mobile phones) plug-in time, battery percentage (SOC) at plug-in time, plug-out time and number of loads connected were randomized. From the outcome of this chapter, the sub-question below is answered.

“What is the technical efficiency and energy savings of 350 V_{dc} LVDC grid installed in the DC Office project?”

For answering this question, three cases were formulated. The ACTube case from LVAC experiment, the DCLED case from LVDC experiment and the ACLED case assumed for LVAC grid using LVDC experimental results.

Technical efficiency:

The overall efficiency of LVAC grid (ACTube case) calculated from experimental and a year-long profile is 88.16% and for LVDC grid (DCLED case) is 94.83%. For the assumed ACLED case, the overall efficiency of LVAC grid is 88.67%. The maximum difference in efficiency of around 6.66% is observed replacing LVAC grid (ACTube) with LVDC grid (DCLED) from this particular thesis.

Table 6.1: Overall technical efficiency of three cases

Cases	Overall efficiency (%)
ACTube (LVAC)	88.17
ACLED (LVAC)	88.67
DCLED (LVDC)	94.83

Energy Savings:

In terms of energy savings, it is calculated that LVDC grids (DCLED) saves 2013 kWh/year when LVAC grid (ACTube) is replaced. And when ACTube case (LVAC grid) is replaced with ACLED case (LVAC grid) then also 1854 kWh/year is saved. But the results ultimately show that DCLED (LVDC grid) achieves more energy savings among all the cases.

Table 6.2: Energy savings replacing ACTube case (LVAC)

Cases	Overall energy consumption(kWh/year)	Energy savings (kWh/year)
ACTube (LVAC)	3944	-
ACLED (LVAC)	2090	1854
DCLED (LVDC)	1931	2013

“What is the cost-savings of the LVDC grid in the DC Office project compared with LVAC grid?”

The cost savings are calculated from the concurred energy savings by replacing the LVAC grid (ACTube case) either to LVDC grid (DCLED case) or to LVAC grid (ACLED case). Considering the dc system lifetime as 12 years, when ACTube case (LVAC) is replaced with DCLED case (LVDC), the

total investment cost is € 1320. At electricity price €0.11/kWh, the cost savings obtained are € 2657.16/12years from which the payback is achievable in 6 years.
On the other hand, when ACTube case (LVAC) is replaced with ACLED case (LVAC) with the same lifetime of 12 years, then the total investment cost is € 1860/12years along with cost savings of €2447.28/12years with payback achievable in 9 years.
From the cost-savings cases discussed in this thesis, the LVDC grid is energy efficient and economical for small office buildings considering lighting, laptops and mobile phones as loads.

Moreover, irrespective of LVAC or LVDC grids, the usage of copper or aluminum as a conductor material for small buildings are studied in terms of cost-savings. From the results, it is identified that the usage of appropriate connector and graded aluminum will reduce the initial investment cost.

All the above-mentioned sub-questions answered the technical efficiency, energy savings and cost-savings of the LVDC grids replacing LVAC grids. In-order to answer the sub-question:

"What is the current scenario for the LVDC grid market in the Netherlands?",
the stake holders, pilot projects, rules & regulations and policies related to LVDC grid were identified. For which, the Function of Innovation System (FIS) approach was utilized.

At present, in the Netherlands the identified stakeholders are Direct Current B.V., Victron energy, ReXel, GTV, STEDIN, Alliander, DC Opportunities and many more as discussed in Function 1. These stakeholders along with research institutions are undertaking several pilot projects in the Netherlands in commercial, residential, educational and horticultural buildings. These stakeholders are provided with sufficient knowledge diffusion through congress, seminars and presentations. As an outcome, the Dutch government had recently implemented NPR 9090 rules and regulations for LVDC grid installations in buildings.

Also, it is identified that there are no rigid incentive policies particularly for supporting the LVDC grids. The government should identify the interests of the stakeholders and provided incentives for market formation and diffusion of LVDC grids into it. It is also identified that the LVDC grids have a positive effect on the energy savings and material savings for big commercial buildings from the results of ABN-AMRO circl building. The acceptance of the LVDC grid from the research of the psychology department in Leiden university shows a positive impact among people in residential buildings. Meanwhile, the knowledge diffusion about the LVDC grids among the people, technicians, electricians and engineers are currently lacking.

It is also identified that the existing AC regime infrastructure like STEDIN and Alliander are supporting the LVDC grids and are researching the implementation of the DC micro and nano-grids. Even though, the LVDC grid market is progressing, the interests of the stakeholders are different and thinks only of what benefits them.

Reflections and Recommendations:

The literature existing and discussed in chapter 1 are mostly available for large building applications. Accordingly, this thesis is also an application research using an established methodology for small office buildings. The scope of the thesis is testing and analysis of the installed LVDC grid in the DC Office setup both technically and commercially. The main knowledge gap between the existing literature and the setup is that the thesis deals with first LVDC grid for small office buildings in the Netherlands and also identifying its current market scenario using FIS approach. From the results discussed throughout the thesis and the conclusion, it is observed that the LVDC grid is 6.7% system efficient and 4% energy efficient than LVAC grid for small office buildings. Similarly, in literature [2] for the small residential house, the LVDC grid is 5% system efficient and 5% energy efficient than LVAC grid. This difference may be due to the fact that only lighting, laptops and mobile phones are considered in this thesis whereas in the literature lightings, heat pumps, electric cooking along with PV solar and storage are considered. Also, in this research the reactive losses and its harmonics are not considered because of the nature of DC and absence of reactance. In the commercial potentials, the FIS framework is used for studying the current market scenario of the Netherlands. From the findings of the research, the actor and stakeholders should enforce the government for subsidies and incentives related to DC grids. From this analysis, the technologies related to the DC grid systems are identified along with stakeholders, rules & regulations. For further extensive research work, interconnection between these technologies using the MLP approach along with the FIS approach can be used for stakeholder mapping.

In the DC Office setup installed there are two voltage levels, this thesis has discussed about the $350V_{dc}$. For future work, the $48V_{dc}$ of the DC Office setup has to be tested and verified. Moreover, for the considered $350V_{dc}$ system generation source of PV solar and storage should be considered. In terms of cost savings, the time value of money (TVM), net present value (NPV), and interest rate can be considered for better monetary advantages of LVDC grids in small buildings. An intensive policy analysis and stakeholder analysis related to the LVDC grids should be carried out for identifying the interests of stakeholders related to LVDC grids.

APPENDIX

A. (INITIAL READINGS METHODS AND LIMITATIONS)

Initially, a chart was arranged in each table where people were asked to enter the data such as the device used, plug-in and plug out time. The timing of the same was registered manually, and the values measured by the power loggers at the corresponding time were not so reliable for randomization. Moreover, for the better comparison of LVAC and LVDC grids, the devices used should be same. But all the devices charged in AC in this phase cannot be used in DC. Only specific laptops with USB – C facility can be used. Even finding volunteers using USB – C was difficult. Hence, for better reliability of data, measurements were decided to be done individually.

During the initial phase measurements, FLUKE 435 Series II power loggers were used to measure the input parameters. For the output parameters, the charger cables are cut and connected in series with the multimeter-1 (FLUKE 289 true RMS multimeter (sensitive)) to measure output current and in parallel with multimeter-2 (normal multimeter) to measure output voltage as shown in Figure A.1.

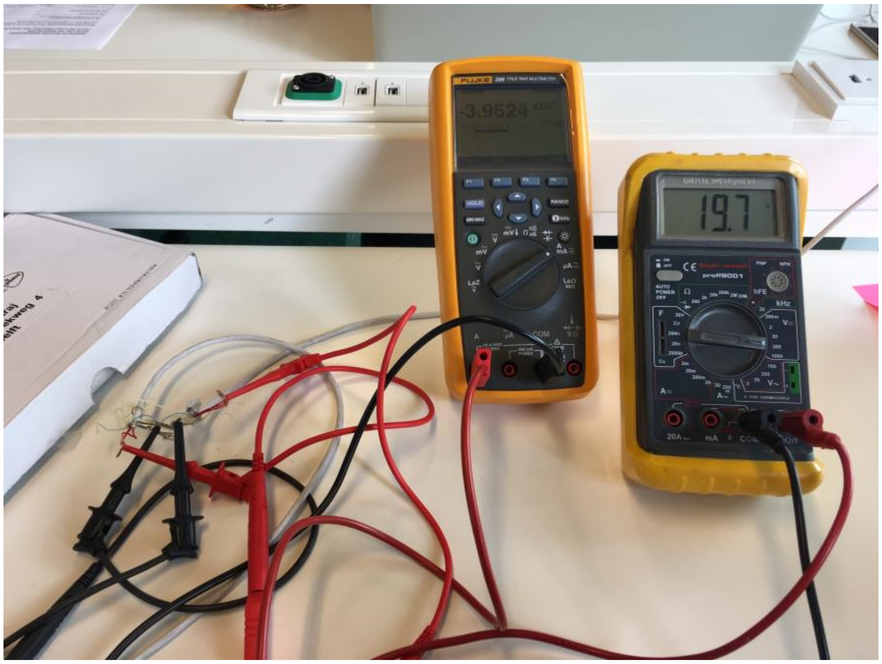


Figure A.1:Initial setup used for measuring AC/DC and DC/DC converter output

The input parameters for both LVAC and LVDC were recorded automatically in the power logger at 1-minute time interval, but the output parameters were measured using the multimeters manually. In the manual recordings, the output voltage and output current from the converter were measured for battery different SOCs (0%, 25%, 50%, 75% and 100%) of the laptops and mobile phone in-order to find the converters efficiencies at each portion of load. The results from this initial phase are shown below in tables for Laptop 1 and laptop 2 both in AC and DC.

Table A.1: AC: Laptop 1: (MacBook Pro 15, with USB-C)

Battery Percentage SOC (%)	**Input parameters recorded in power logger**				**Output parameters measured using multimeters**			
	Voltage $V_{ac,\ in}$	**Current $A_{ac,\ in}$**	**CosΦ**	**Active power in (W_{ac})**	**Voltage out ($V_{dc,\ out}$)**	**Current out ($I_{dc,\ out}$)**	**Power out ($W_{dc,out}$)**	**Adapter Efficiency ($W_{dc,out}/W_{ac,in}$)*100**
0	232.78	0.387	0.88	79.5	19.9	3.604	71.719	90%
25	233.66	0.395	0.89	81.7	19.9	3.712	73,869	90.4%
50	234.46	0.36	0.88	74	19.9	3.301	65.689	88.7%
75	233.12	0.396	0.42	39.2	20.0	1.716	34.32	87.5%
100	233.58	0.358	0.43	35.9	20.1	1.468	29.507	82.2%

Table A.2: DC: Laptop 1: (MacBook Pro 15, with USB-C)

Battery Percentage SOC (%)	**Input parameters recorded in power logger**			**Output parameters measured using multimeters**			
	Voltage $V_{dc,\ in}$	**Current $A_{dc,\ in}$**	**Active power in (W_{dc})**	**Voltage out ($V_{dc,\ out}$)**	**Current out ($I_{dc,\ out}$)**	**Power out ($W_{dc,out}$)**	**Adapter Efficiency ($W_{dc,out}/W_{dc,in}$)*100**
0	349.6	0.228	79.709	19.5	3.547	69.166	86.8%
25	349.58	0.235	82.151	19.5	3.646	71.097	86.5%
50	349.64	0.219	76.571	19.5	3.462	67.509	88.1%
75	349.68	0.115	40.213	19.9	1.761	35.044	87.2%
100	349.78	0.105	36.727	19.9	1.467	29.193	79.5%

Table A.3: AC: Laptop 2: (MacBook Pro 13, with USB-C)

Battery Percentage SOC (%)	Input parameters recorded in power logger				Output parameters measured using multimeters			
	Voltage $V_{ac, in}$	Current $A_{ac, in}$	CosΦ	Active power in (W_{ac})	Voltage out $(V_{dc, out})$	Current out $(I_{dc, out})$	Power out $(W_{dc,out})$	Adapter Efficiency $(W_{dc,out}/W_{ac,in})*100$
0	235.55	0.476	0.45	50.3	20.1	2.21	44.421	88%
25	235.43	0.492	0.45	51.7	20.1	2.286	45.95	89%
50	236.16	0.35	0.44	37.5	20.2	1.641	33.148	88%
75	236.53	0.248	0.41	24.1	20.3	1.049	21.295	88%
100	234.59	0.217	0.41	21.1	20.3	0.867	17.6	83%

Table A.4: DC: Laptop 2: (MacBook Pro 13, with USB-C)

Battery Percentage SOC (%)	Input parameters recorded in power logger			Output parameters measured using multimeters			
	Voltage $V_{dc, in}$	Current $A_{dc, in}$	Active power in (W_{dc})	Voltage out $(V_{dc, out})$	Current out $(I_{dc, out})$	Power out $(W_{dc,out})$	Adapter Efficiency $(W_{dc,out}/W_{dc,in})*100$
0	349.46	0.15	52.419	19.9	2.27	45.173	86%
25	349.46	0.156	54.516	19.9	2.38	47.362	87%
50	349.42	0.12	41.930	20.2	1.85	37.37	89%
75	349.52	0.073	25.515	20.3	1.05	21.315	84%
100	349.5	0.066	23.067	20.1	0.913	18.351	80%

These measured data were verified using the Fluke Scopemeter, were both input and output are recorded manually. From the scopemeter results, it was identified that the previously obtained results have manual recording errors and the measurement technique discussed in chapter 2 is finalized.

The scopemeter can only record four parameters. So, two parameters were allocated for input and two for output. Mainly, the active power is selected for both input and output in-order to check the efficiency of the converter effectively. Also, for further comparison the AC/DC and DC/DC converters for laptop 1 were tested in the Lab of a company named Direct Current B.V. The results from the labs shown in Figure A.2 were similar to the scopemeter results.

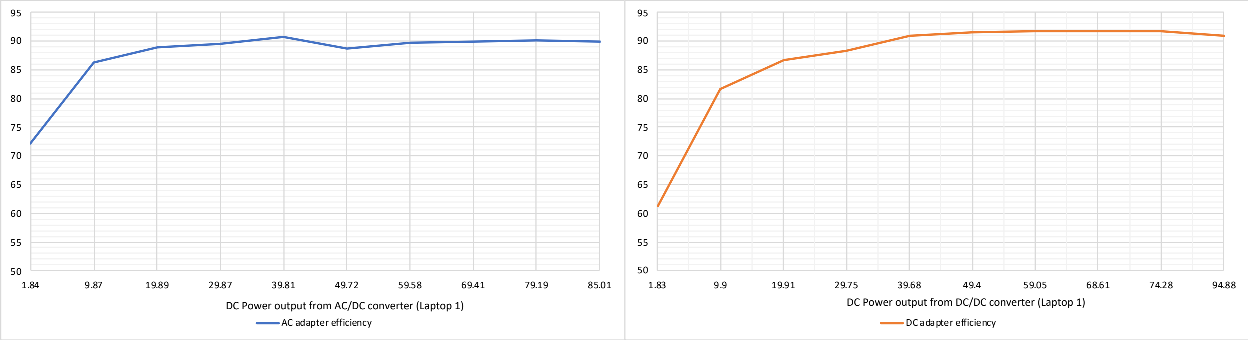


Figure A.2: Measurements from Direct Current B.V. labs for verification

The Figure A.3, Figure A.4, Figure A.5 and Figure A.6 are the active energy measured (Wh/min) used as in input for randomization. The measured values are for 1 day throughout the working hours (10 hours) of the DC Office.

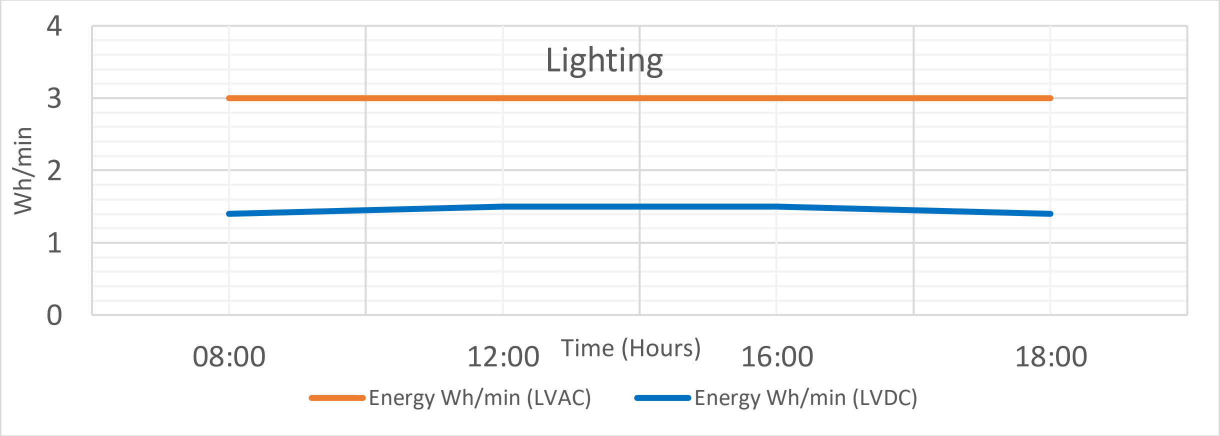


Figure A.3: Measured data for Lighting (Wh/min)

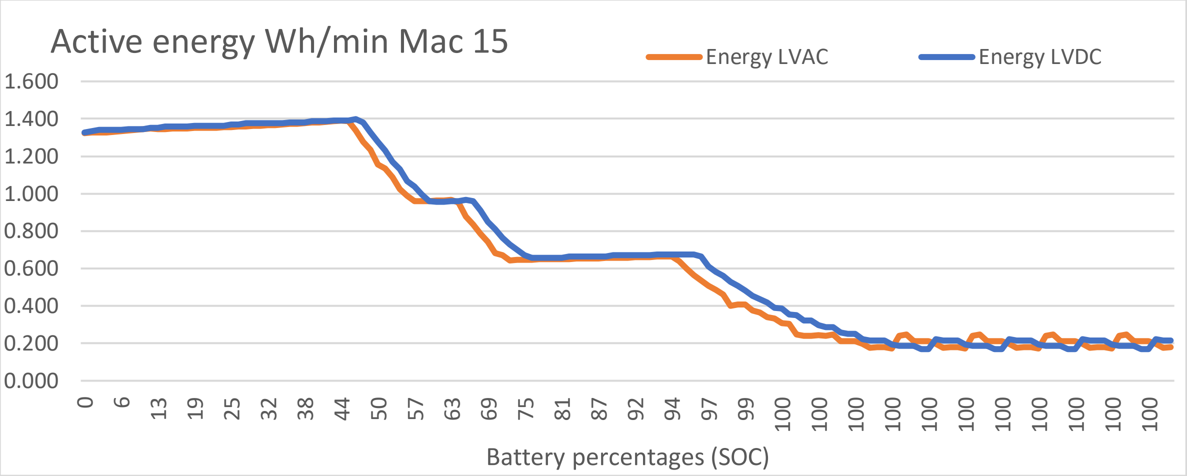


Figure A.4: Measured data for Laptop 1 (Wh/min) (Mac 15)

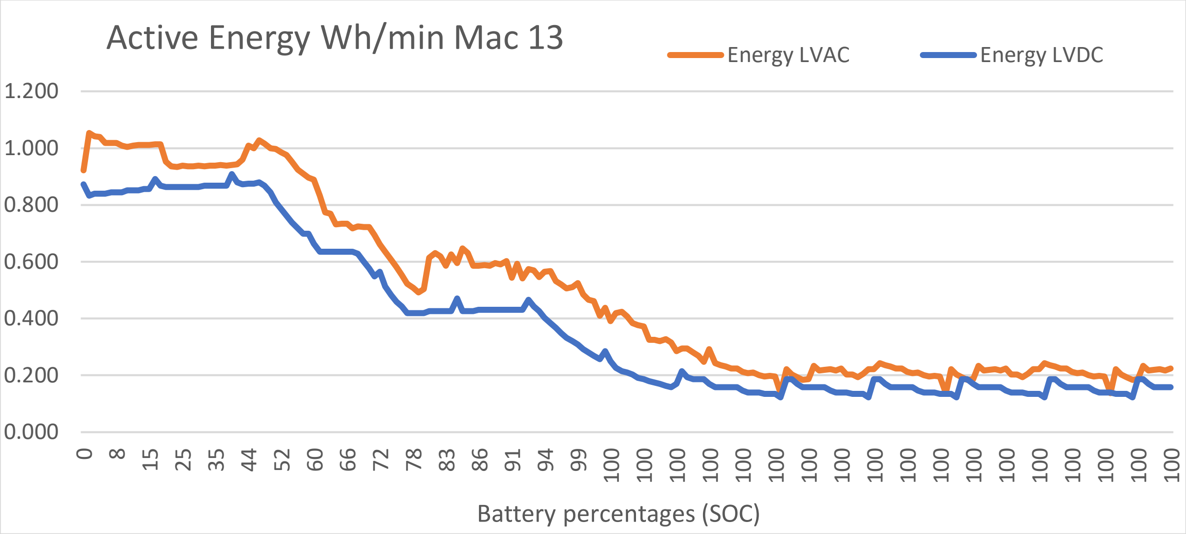


Figure A.5: Measured data for Laptop 2 (Wh/min) (Mac 13)

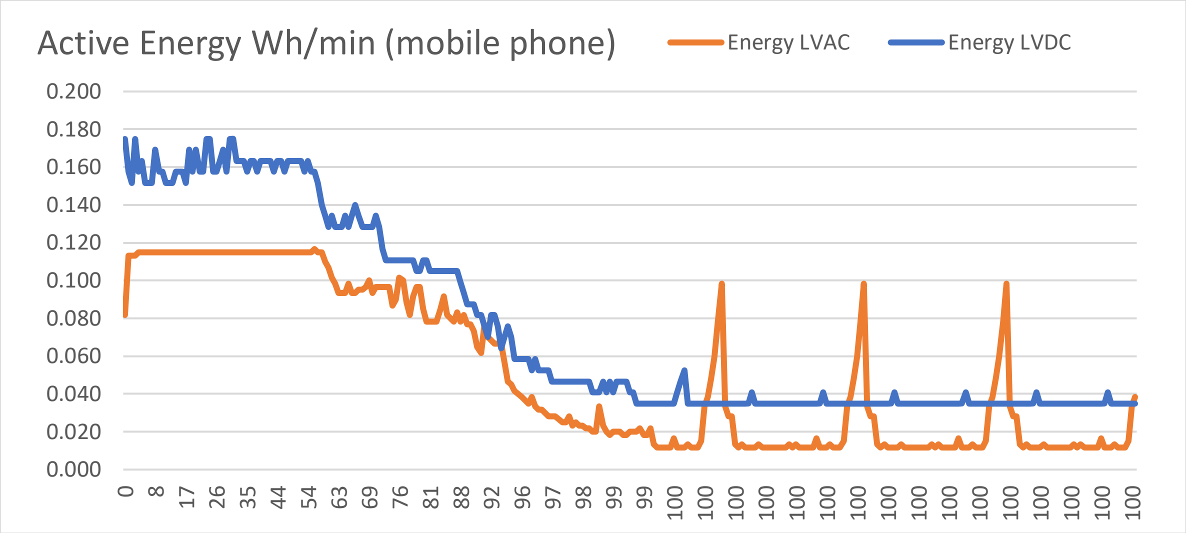


Figure A.6: Measured data for Mobile (Wh/min) (iPhone)

B. APPENDIX (Wire selection for copper and aluminum)

The electric cables are the veins of an electrical grid system, cables carry electricity and if it is not selected appropriately it can cause significant power losses. In present market, the most commonly used commercial cable materials for electrical wirings are copper and aluminum. From which, the aluminum cables are used for High Voltage AC and Medium Voltage AC lines, whereas copper is used for LVAC lines according to the material properties and cost-effectiveness. Correspondingly, recent study on the LVDC grids on buildings say that the LVAC cables in buildings can be used as LVDC cables (up to 1500V_{dc}).[9][79]

When these cables are utilized for AC and DC distribution in buildings, irrespective of the materials, there are several losses that should be considered according to the nature of AC and DC. When an AC is supplied in cables, there are magnetic losses, resistive losses (I^2R), skin effect, proximity effect, dielectric losses. Likewise, when DC is supplied there is resistive loss (I^2R) in a cable. According to the research [79], the materials are considered non-magnetic in LVs and magnetic loss is neglected due to no hysteresis cycle. Also, the dielectric losses can be neglected for LVs. Meanwhile, the skin effect is caused by the magnetic field of the conductor when AC is supplied at 50 or 60 Hz frequency. This is known as auto-induction phenomena and denoted using skin depth.

This skin depth is the reduced area in which the AC electricity travel increasing the resistance of the cable. Likewise, the proximity effect occurs in the cable bundles depending on the spacing of cable arrangements. These skin effect and proximity effect along with actual cable resistance (R) determines the effective resistivity (R_{ac}) of the cable for AC transmission. But for DC transmission the actual resistance (R) is the effective resistance (R_{dc}). From the results of the research [79], it shows that the skin effect and proximity effect are not significant for single phase systems with small cross sectional area as shown in Figure B.1. Thus, for the scope of the DC Office research, it is considered that R_{ac} is same as R_{dc} and accordingly the energy savings are discussed in both technical and economical perspectives. The following section explains the comparison between the usage of copper and aluminum for LVDC distribution in buildings.

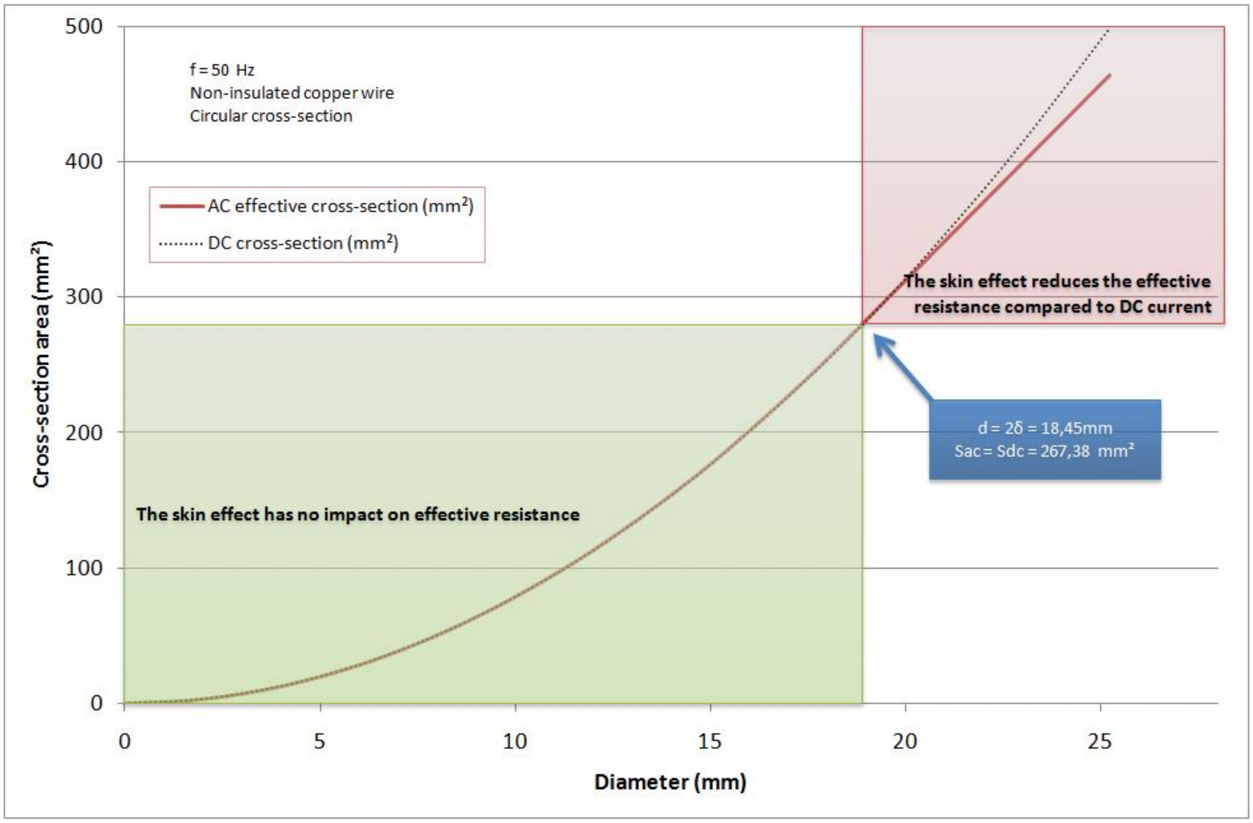


Figure B.1: wire cross-sectional area (mm2) vs skin effect

The basic material properties of an electrical conductor are electrical resistivity, tensile strength, thermal expansion and density. According to these properties, considering the safety and standards, the usage of copper and aluminum for electrical supply are discussed in regulation code IEC 61439-1 and -6 [23]

In this Appendix, the electrical resistivity of the two materials will be briefly discussed along with the selection criteria of a wire for buildings while using AC and DC supply. For the usage of copper and aluminum wires there are certain advantages and disadvantages as shown in Table B.1. [80]

Table B.1: Property advantages and disadvantages of copper and aluminum

Copper		Aluminum	
Advantages	Disadvantages	Advantages	Disadvantages
• Low electrical resistance. • High tensile strength. • Long life. • Less thermal expansion	• High cost. • Three times heavier than aluminum.	• Low Cost. • Light weight. • Electrical grade aluminum alloys have tensile strength close to copper. • Tin is plated over aluminum conductors to ensure the direct connection between aluminum and copper.	• High electrical resistance compared to copper. • Pure aluminum has 2 times less tensile strength than copper. • Oxidation occurs when copper connectors are used for aluminum cables. • Thermal Expansion

For selection of wires either to transmit AC or DC in building there are certain procedures being followed. Those procedures are as follows:

Size of the wire:

The designers choose the appropriate wire diameter corresponding to the current carrying capacity (ampacity). The size of the wire is important in-order to reduce the resistance and power losses in cables according to the maximum current requirement in the power system. Keeping the resistance and ampacity constant, according to the material properties, aluminum diameter should increase to 1.26 times than copper of same length.[23]. The wire sizes are denoted using AWG (American Wire Gauge) or Square Gauge (mm^2).

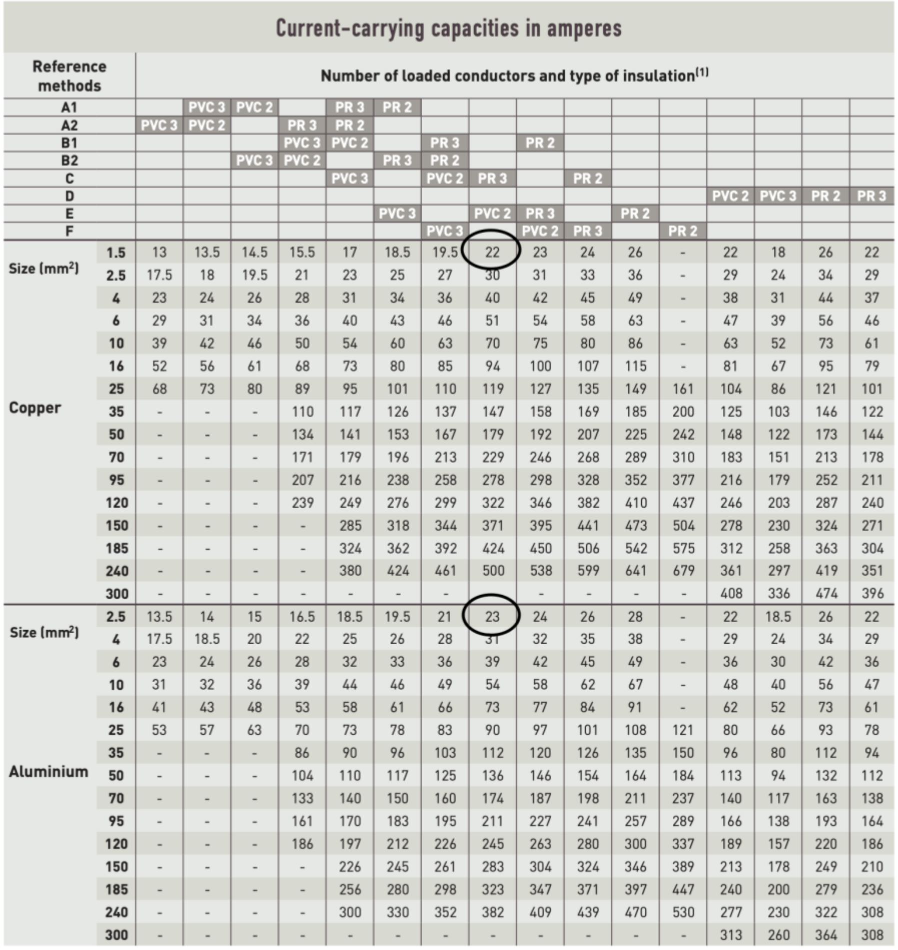
Type of the wire design:

There are several wire designs 2 cores, 3 cores, 4 cores and multi-cores according to the nature and functions. Usually these cables are selected for AC systems, according to the single-phase or three phase AC systems and unipolar, DC bipolar systems For DC systems and type of buildings.

Material of the wire:
As stated above, the material for the wire either Copper or Aluminum is selected according to the voltage levels.

Insulation type:
The most commonly used insulation type for both AC and DC are Polyvinyl chloride (PVC), Halogen Free Resistant (HFFR) or reticulated polyethylene (XLPE/PR)

From the Legrand report [26], the reference methods of either C or E can be selected which is similar to DC Office setup. From the details of the ampacity (22A) of the multi-core wire installed in DC Office, this Figure B.2 shows the relevant multi-core wire and its size in aluminum.



Current-carrying capacities in amperes

Reference methods		Number of loaded conductors and type of insulation[1]															
A1			PVC 3	PVC 2		PR 3	PR 2										
A2		PVC 3	PVC 2		PR 3	PR 2											
B1					PVC 3	PVC 2		PR 3		PR 2							
B2				PVC 3	PVC 2		PR 3	PR 2									
C						PVC 3		PVC 2	PR 3		PR 2						
D														PVC 2	PVC 3	PR 2	PR 3
E							PVC 3		PVC 2	PR 3		PR 2					
F								PVC 3		PVC 2	PR 3		PR 2				
Size (mm^2)	1.5	13	13.5	14.5	15.5	17	18.5	19.5	22	23	24	26	-	22	18	26	22
	2.5	17.5	18	19.5	21	23	25	27	30	31	33	36	-	29	24	34	29
	4	23	24	26	28	31	34	36	40	42	45	49	-	38	31	44	37
	6	29	31	34	36	40	43	46	51	54	58	63	-	47	39	56	46
	10	39	42	46	50	54	60	63	70	75	80	86	-	63	52	73	61
	16	52	56	61	68	73	80	85	94	100	107	115	-	81	67	95	79
	25	68	73	80	89	95	101	110	119	127	135	149	161	104	86	121	101
Copper	35	-	-	-	110	117	126	137	147	158	169	185	200	125	103	146	122
	50	-	-	-	134	141	153	167	179	192	207	225	242	148	122	173	144
	70	-	-	-	171	179	196	213	229	246	268	289	310	183	151	213	178
	95	-	-	-	207	216	238	258	278	298	328	352	377	216	179	252	211
	120	-	-	-	239	249	276	299	322	346	382	410	437	246	203	287	240
	150	-	-	-	-	285	318	344	371	395	441	473	504	278	230	324	271
	185	-	-	-	-	324	362	392	424	450	506	542	575	312	258	363	304
	240	-	-	-	-	380	424	461	500	538	599	641	679	361	297	419	351
	300	-	-	-	-	-	-	-		-	-	-	-	408	336	474	396
Size (mm^2)	2.5	13.5	14	15	16.5	18.5	19.5	21	23	24	26	28	-	22	18.5	26	22
	4	17.5	18.5	20	22	25	26	28	31	32	35	38	-	29	24	34	29
	6	23	24	26	28	32	33	36	39	42	45	49	-	36	30	42	36
	10	31	32	36	39	44	46	49	54	58	62	67	-	48	40	56	47
	16	41	43	48	53	58	61	66	73	77	84	91	-	62	52	73	61
	25	53	57	63	70	73	78	83	90	97	101	108	121	80	66	93	78
	35	-	-	-	86	90	96	103	112	120	126	135	150	96	80	112	94
Aluminium	50	-	-	-	104	110	117	125	136	146	154	164	184	113	94	132	112
	70	-	-	-	133	140	150	160	174	187	198	211	237	140	117	163	138
	95	-	-	-	161	170	183	195	211	227	241	257	289	166	138	193	164
	120	-	-	-	186	197	212	226	245	263	280	300	337	189	157	220	186
	150	-	-	-	-	226	245	261	283	304	324	346	389	213	178	249	210
	185	-	-	-	-	256	280	298	323	347	371	397	447	240	200	279	236
	240	-	-	-	-	300	330	352	382	409	439	470	530	277	230	322	308
	300	-	-	-	-	-	-	-	-	-	-	-	-	313	260	364	308

Figure B.2: Wire size in copper and aluminum

C. INTERVIEW

Interviewer: Ronald Fransen (Secretary treasurer, Foundation DC Netherlands)
Guest speaker: Harry Stokman (DC Expert, CEO of Direct Current B.V.)

Q1: In 2010 – 2011, Netherlands proposed a scheme for carbon neutral residential areas (Woonwijk), Why this scheme is not yet approved? Is the vision still true?

Answer:
Vision is true, and yet the work has to be proceeded towards it. The delay in the achievement of the vision is due to optimal usage.

- Optimal usage individually is good. But all together as a system, it is not well established as a structure.
- The organization has to supervise, and system optimization has to be happened in-order to save the energy as a system.
- While using DC, it is a very simple to operate and robust in design. The system is easy to handle even during faulty conditions. The collapse of whole system due to a single link failure is less likely in DC system.

The load variation in the present AC system increases the voltage fluctuation and suffer losses due to lack of robustness. To transmit the same differences over AC, zone has to modify the frequency parameters and that is considerably more difficult to realize in practice.

Q2: 7-8 years ago you mentioned that the reason the industry is not taking up DC yet is because the energy market/ business is very conservative? I.e. less likely to change fast. Is it still no conservative?

Answer:
In my time as a grid manager (?) we had these discussions but never reached a conclusion. The grids and the organizations that manage the grids (or energy providers) have so much investment in the current AC transmission system that suggesting a change is not easy. Return on investments has to justify doing away with the existing infrastructure.

Q3: Do you still believe the vision (of changing transmission systems) will happen?

Answer:
Used an example from Almere in the past to show how each micro-grid can manage its energy needs independently. And still be tied in to a bigger grid framework. Thus each “polder” had a certain autonomy to make their energy-related decisions.
SlimNET did this integration (refer Almere Expt.)
To prove that changes have to start local and be integrated into a bigger, smarter system.

Q4: If it is so logical and evident, what is holding us back?

Answer:
Knowledge. This has to involve people who think on a system-level and not in small boxes. Each stakeholder has its own interests and thinks only of what benefits them. To integrate the system as a whole, this has to change and a broader, helicopter vision needs to follow.

TenneT, Adel, Rexel etc. are in the discussion about installing DC systems.

All aspects of the energy transmission link still work as separate islands. Clients will like to invite other energy transmission alternatives, but the providers would like to stick with a reliable formula that works in covering their costs.

“If the links are not broken, don’t change it”. Cables of 20 years old are still used in transmission because they are functional, if not the most optimal.

Therefore, the micro-grid structure is preferred because it can work without disrupting the existing system. Inclusion of solar panels on house rooftops and the integration of such energy back to the grid was presented as an example.

Q5: 8 years ago, you had also mentioned that in the future people will pay not for the energy costs but for the infrastructure?

Answer:
In Finland, it is already in place. There are concessions in place for land owners and others, including the possibility to invest in the energy infrastructure. 2/3rd of the costs are written down to the systems/ infrastructure.

Q6: Public management of energy is the way to go?

Answer:
Yes.

Q7: Is there a storage scheme possible with energy? Surplus energy that can be saved (or not used) and to be tapped in later? Day/ night and summer/ winter balance?

Answer:
There are benefits to be had. But a smarter overall system needs to be in place to tap the most into energy savings. Infrastructure should be built to that end.

Q8: What in your opinion is the role of the Govt. in this?

Answer:
NL is already quite advanced in that. The Govt. is well-integrated into social schemes. They have a huge role to play along with the energy providers to optimize the systems and the way energy is transmitted.

There are two departments – one for the cables(providers) and the other for system operations. System operation make appointments with the Clients and the providers to make sure that transmission of electric energy is going fine.

Q9: How will the cooperation with other countries in Europe work?

Answer:
Harry himself is in a Systems' Committee that is a sort of a match-maker (DCVA System). Taking different stakeholders into account and developing and maintaining a transmission system based on all-round parameters. Chairpersons of all the technical committees worldwide will come together next year to develop this system further.

350 V is very handy for DC applications. 380 V, the American standard, has technical challenges to be used for DC applications.
700 V, 1400 V etc. are also other options, but less preferred.

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