Supporting the transition to DC micro grids in the built environment

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Supporting the transition to DC micro grids in the built environment

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January, 2017
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SMART ENERGY BUILDINGS & CITIES

Supporting the transition to DC micro grids in the built environment

By

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A dissertation submitted in partial fulfillment of the requirements for the degree of Professional Doctorate of Engineering

The design described in this thesis has been carried out in accordance with the TU/e Code of Scientific Conduct

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Abstract

Currently, the energy sector is in a phase of transition triggered by global concerns like growing demand of electrical energy, energy conservation, clean environment and energy costs. The expected increase in the number of direct current (DC) loads in conjunction with the integration of photovoltaics (PV) and storage into the grid have increased the interest in low voltage DC (LVDC) as a solution for bringing safe, efficient and green electricity to all.

By distributing DC power to DC devices instead of converting it to alternating current (AC) along the way, it’s possible to avoid substantial energy losses that occur every time electricity is converted.

DC-Flexhouse is a TKI-iDEEGO project that focuses on the introduction of DC technology in the built environment. Five companies (ABB BV, Direct Current BV, IBC Solar BV, EP and Siemens Netherlands BV) and two research organizations (NEBER and the Hague University) joint their forces to develop a plug-and-play renovation method for integrating DC technology in buildings. The goal is to minimize the levels of intervention by utilizing the existing electrical infrastructure.

Although DC seems to be a promising solution for more sustainable energy systems, the business case is still debatable due to both technology- and market-related challenges. The current energy infrastructure is predominantly based on AC, manufacturers produce devices based on AC standards and people are using many AC products across a long life span. There is no explicit market need and as a consequence, managers might quickly evaluate the development of LVDC products as a bad business proposal.

This Smart Energy Buildings and Cities (SEB&C) Professional Doctorate in Engineering (PDEng) project is a contribution to the DC-Flexhouse project on behalf of ABB BV. It targets to support the transition to DC micro grids by demonstrating the future market potential and proposing enabling strategies for successful market introduction. The aim of this project is to assess the market potential of DC applications in the built environment and develop a framework that leads to a commercial success.

In order to assess the future market potential of DC, the current situation and trends in the energy sector are analyzed based on the Multi-level perspective (MLP) framework [1] [2]. The MLP describes the drivers that lead to the breakthrough of innovations and has been fruitfully applied in studies of transitions to sustainability [1]. This analysis demonstrates that although there is no explicit market need at the moment, DC technology fits within the overall energy transition. Investing in R&D activities at this moment will allow ABB and other involved companies to capitalize on the market potential in the future.

Based on the transition management and innovation literature, a set of propositions towards the successful commercialization of DC is developed. The breakthrough of innovations starts from early niche markets and/or technological niches. Groups of early adopters are identified by combining the value proposition of DC with needs and perceived values in different market segments. Members of the DC-Flexhouse project can experiment with different technology-market combinations and improve both technology and business processes based on lessons learned.

A case study is performed to assess the value proposition of DC for residential buildings. The case study reveals that the real potential of DC lies in the existence of a DC distribution grid. Therefore, grid operators are key actors for the success of DC. Further research is needed to assess whether DC constitutes an economically feasible solution for the distribution level. Alliander is already experimenting with DC distribution grids and plans to launch projects for the connection of residential buildings within 2017.
In the case of existence of a DC distribution grid, the capital cost of a PV installation with battery storage decreases by 8% and 46% for existing and new buildings respectively when compared to reference AC-based systems. This also implies that DC facilitates further market penetration of PV and battery storage systems. DC can be especially beneficial for battery technologies that still constitute a niche market.

Overall, at the time this PDEng project is conducted it appears to be difficult to gauge the market growth. However, the analysis of the current situation and future trends reveals that although the market potential of DC is highly debatable at this moment, DC innovation fits within the overall developments in the energy sector and can have a market potential in the future if managed properly. ABB and other parties that want to promote DC technology should first target to build strategic alliances with co-innovators and then find frontrunners that are willing to invest and adopt the innovation. Niche markets such as new buildings might initially not generate a substantial level of profit for the actors in the value chain, but entering these niche markets now will facilitate broader market development at a later stage.
Acknowledgments

These last two years have been an incredible journey. I would really like to express my gratitude to all the people that guided me, inspired me and supported me throughout this journey. Without their assistance, the successful completion of this project and of the PDEng degree would not be possible.

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Evdokia Ploumpidou

January 11, 2017
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List of abbreviations

AC  Alternating Current
BAN  Building Area Network
BENG  Bijnna-Energieneutrale Gebouwen (nearly zero-energy buildings)
BMS  Building Management System
CO2  Carbon dioxide
DC  Direct Current
DG  Distributed Generation
DR  Demand Response
DSM  Demand Side Management
DSO  Distribution System Operator
DT  Design Thinking
EES  Electrical Energy Storage
EPC  Energy Performance Contracting
EPN  Energy Performance Standards
EVP  Ecosystem’s Value Proposition
ESCos  Energy Service Companies
EV  Electric Vehicle
FAN  Field Area Network
HAN  Home Area Network
HEMS  Home Energy Management System
IAN  Industrial Area Network
ICT  Information and Communication Technologies
IEC  International Electrotechnical Commission
LED  Light-emitting Diode
LVDC  Low Voltage Direct Current
MLP  Multi-level Perspective
MPPT  Maximum Power Point Tracker
NAN  Neighborhood Area Network
PFC  Power Factor Correction
PLC  Power Line Communication
PoE  Power over Ethernet
PRP  Programme Responsible Party
PV  Photovoltaic
SEG  System Evaluation Group
TCO  Total Cost of Ownership
TM  Transition Management
TSO  Transmission System Operator
TVO  Total Value of Ownership
WAN  Wide Area Network
Structure of the report

This report is a contribution to the DC-Flexhouse project through a collaboration between Eindhoven University of Technology and ABB BV, within the framework of the Smart Energy Buildings and Cities (SEB&C) Professional Doctorate in Engineering (PDEng) program. The report consists of three parts: A) Towards DC micro grids in the built environment (main outcome), B) Case study for residential buildings and C) Business Plan. Each part contains a separate table of contents and can be read autonomously from the others. For confidentiality reasons, Part C is not publicly available, therefore this report version includes only Parts A and B.

Part A provides an assessment of the future market potential of low voltage DC (LVDC) products and a set of propositions that form a strategy for the transition to DC micro grids. Companies and organizations involved in the DC-Flexhouse projects can follow this propositions to steer activities towards the commercial realization of DC micro grids. The proposed strategy is intended to be applied not only to DC-Flexhouse project but also to future projects for the development of DC technology.

Part B investigates the business case of DC for a specific customer segment (residential building) in order to validate the value proposition and the business opportunities that arise within the DC context for involved industries (mainly manufacturers and companies active in the construction sector). The business case focuses on a cost-benefit analysis of different DC system configurations taking into account energy savings and capital costs. The case study was conducted to support the implementation of both Part A and Part C.
Part A: Towards DC micro grids in the built environment
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1. Introduction
1.1 Project background
Currently, the energy sector is in a phase of transition. This transition has been triggered by concerns about growing energy demand, energy costs and environmental issues [3]. The European Union (EU) has set its target for a 20% cut in greenhouse gas emissions, 20% share of renewables and 20% improvement in efficiency [4]. Buildings are responsible for 40% of energy consumption and 36% of CO2 emissions in the EU [5] [6]. Therefore by improving the energy efficiency of buildings, substantial energy savings and lower CO2 emissions can be achieved. More and more, effort is invested in the construction and renovation of buildings in order to decrease their energy consumption. These investments are mainly heat related like better insulation and heat pumps. As these techniques decrease our demand for heat, the drive to more efficiency also shifts to electricity.

Today our electricity is predominantly powered by alternating current (AC). However, lots of the appliances we use, such as electronics and lights with light-emitting diode (LED) technology, work internally on direct current (DC), while it is projected that the number of these appliances will increase in the near future [7]. Within the next 20 years we could definitely see as much as 50% of our total loads be made up of DC consumption [8]. Another contributor to the increase in DC consumption is the ongoing electrification of mobility (Electric Vehicles (EVs)) [9] [10]. EVs charge on DC and require substantial amounts of power. In the current situation, all these loads need AC to DC converters to be connected to the AC grid and these components introduce power losses to the system. At the same time, it is expected that a large part of the renewable energy will be produced from decentralized sources [11]. Photovoltaics (PV), which is the most common renewable source in the built environment [12] generates DC voltages, while the most common storage technologies also use DC voltages. In order to integrate these technologies to the existing AC grid, again there is a need for converters that introduce more power losses.

This situation has increased the interest in low voltage DC (LVDC) as a solution for bringing efficient and green electricity to all. By distributing DC power to DC devices instead of converting it to AC along the way, it’s possible to avoid substantial energy losses that occur every time electricity is converted. DC technology is already being explored for the electrification of rural off-grid areas in developing countries with energy generated by renewable energy sources (RES) [13] [14] [15].

In this context, the implementation of the DC-Flexhouse project was initiated. DC-Flexhouse is a project funded under the national TKI-iDEEGO program. Five companies (ABB BV, Direct Current BV, IBC Solar BV, EPM, Siemens Netherlands BV) and two research organizations (NEBER, the Hague University) joint their forces to develop a renovation methodology for integrating DC technology in buildings. Project partners target to minimize the levels of interventions by utilizing the existing electrical infrastructure of the building. The main objectives of DC-Flexhouse project are the development of a prototype system and the investigation of the business case of DC for end-users and actors within the value chain.

The prototype will be developed, installed and tested in one of the buildings of the developing living lab area called the District of Tomorrow ² (De Wijk van Morgen) which is located in Heerlen. In the project also participates a neighborhood cooperative (Vrieheide cooperatie) in order to address the aspect of social acceptance.

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1 The Netherlands is the European frontrunner in EV uptake with more than 4% of new car sales in 2013 [91].
2 More information about the ‘District of Tomorrow’ programme can be found online: [http://www.dewijkvanmorgen.nl/](http://www.dewijkvanmorgen.nl/)
This PDEng project is a contribution to the DC-Flexhouse project. It is conducted in the first year of the DC-Flexhouse project (Figure 1). The findings can be used by project partners for further development of the DC-Flexhouse project, as well as for the implementation of future projects in the DC field.

![Timeline of DC-Flexhouse and PDEng projects](image)

**Figure 1. Timeline of DC-Flexhouse and PDEng projects**

### 1.2 Problem description

The installation of DC micro grids in buildings is a radical innovation. That is, it is a transition that requires the shift from the predominantly alternating current (AC) energy supply infrastructure to an alternative one that also includes DC systems. This transition is challenging for developed countries such as the Netherlands, because the largest part of the energy sector is engineered to run on AC. Therefore, currently there is no explicit demand for DC and no identified problem (e.g. with AC) that DC solves. As a result, various actors within the value chain might not recognize the benefits of this transition; a fact that might result in the lock-out of DC innovation.

Companies involved in the DC-Flexhouse project target to get an insight into the needed technology developments and the market potential in order to update their portfolio of products and services. The challenge is that although DC contributes to a more sustainable world, adoption by the market is still questionable. For sustainable innovations, markets often do not exist (benefits are at the collective level of societies, no individuals are willing to invest). Markets have to be created: market and technology develop in a process of co-evolution [16].

In this respect, it can be clearly seen that there is a gap between the desired vision for DC and where we stand today. This PDEng project explores the potential of the transition from an AC energy infrastructure to an alternative infrastructure that also includes DC energy systems. In line with the DC-Flexhouse project objectives, this project contributes to the investigation of the business case of DC. It looks into trends in the energy sector in order to assess the future market potential and proposes a framework to facilitate market introduction taking into account both technology and market aspects.

![Position of PDEng project relative to DC-Flexhouse project](image)

**Figure 2. Position of PDEng project relative to DC-Flexhouse project. The Technology Readiness Level (TRL) scale is a metric for describing the maturity of a technology (distinction between phases is adopted from the European Commission’s guidelines [17]. The key output of DC-Flexhouse project is a prototype system design (TRL 6). This PDEng project focuses on how market introduction can be enabled by taking into account both technology and market aspects.**
1.3 Project scope and objectives
This project targets to support the transition to DC micro grids in the built environment by investigating enabling strategies for successful market introduction. More specifically, the following objectives are identified:

- **Identify the benefits of DC compared to AC**
  The identification of the benefits of DC as opposed to AC helps DC-Flexhouse project partners to clearly demonstrate them to actors whose involvement is essential for the success of the transition.

- **Proposing strategies for the transition**
  This report can be used by companies and research organizations involved in DC-Flexhouse project to steer activities towards the commercial realization of DC micro grids. Proposed strategies are intended to be applied not only to DC-Flexhouse but also to future DC projects.

- **Assessing the market potential**
  The market opportunities that arise within the DC innovation are investigated based on future trends and assumptions regarding the financials with the development of a business plan\(^3\). The business case of DC for involved industries is validated by a case study that examines the cost-effectiveness of DC for residential buildings\(^4\).

The technical design of the DC prototype system that is being designed within the DC-Flexhouse project is out of the scope of this study. This PDEng project focuses on the development of a framework that leads to a commercial success.

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\(^3\) The business plan is not publicly available.

\(^4\) The case study can be found on Part B of the present document.
2. Methodological approach

2.1 Theoretical background

The integration of DC micro grids in buildings is a radical innovation and requires a transition process in the energy sector. Literature on transition studies was reviewed in order to understand how radical innovations penetrate the market and to apply respective principles in our case: the transition to DC. Transition theory can be seen as a framework for finding solutions to persistent and complex societal problems [18] [19]. The Multi-level perspective (MLP) and the Transition Management (TM) are two concepts applied within the context of this study. The MLP is used to understand how transition processes work and identify how such an innovation can potentially challenge the existing energy regime, while TM provides guidelines aimed at facilitating and directing processes towards the commercialization of DC through the creation of multi-actor networks.

2.1.1 Multi-Level Perspective

The MLP is an approach developed by Geels [19] that targets to research and describe transition processes to sustainable energy systems. The MLP identifies three different levels when it comes to radical transformations: the niches (micro-), regime (meso-) and sociotechnical landscape (macro-level). These three levels interact with each other in different ways. The MLP emphasizes the importance of observing the interactions among these three levels and sets a theoretical framework for explaining transition processes towards sustainability.

**Niches** are highly dynamic systems where radical innovations emerge and disappear, where ideas and technologies are found and tested before they (might) enter a broader market [20]. In this application domains, users have different preferences than mainstream users. Historical examples that support this assumption are the application of solar cells in space and mobile phones for business men. These early adopters are willing to pay a higher price and support an emerging innovation because of particular benefits they gain from it. When it comes to sustainable innovations this is not always the case [16]. Early niche markets often do not exist (benefits are at the collective level of societies, no individuals are willing to invest). Markets for sustainable innovations have to be created: market and technology develop in a process of co-evolution [21]. In the context of social learning, by actually using an innovation, users create or learn about new needs, policy makers create regulatory frameworks that fit the innovation and industrial actors learn to improve the innovation and reduce costs. Scholars have called these special niche markets technological niches [16]. Technological niches become operational through a series of protected test-beds such as pilot and demonstration projects that are often financially supported by public subsidies. DC-Flexhouse project can be considered as a first test bed towards this direction.

**Regimes** are much less dynamic structures than niches with a set of different rules than orient and coordinate the socio-technical system. Examples of regime rules are cognitive routines and shared beliefs, capabilities and competencies, lifestyles and user practices, favorable institutional arrangements and regulations, and binding contracts [1]. Typical effects resulting from these rules are technological lock-ins, vested interests defending a certain status and reproduction instead of innovative alternatives. Innovation occurs incrementally, with small adjustments accumulating into stable trajectories. These trajectories occur not only in technology, but also in cultural, political, scientific, market and industrial dimensions. While science, technology, politics, markets, user preferences and cultural meanings have their own dynamics, coordinated by different sub-regimes, they also interpenetrate and co-evolve with each other. According to the MLP transitions can be defined as shifts from one regime to another regime, driven by dynamics from the micro- or the macro-level. Thus, regimes are of major interests from a research perspective on transitions [20].
The socio-technical landscape is the wider context which influences niche and regime dynamics [1] and refers to events and development is the exogenous environment such as demographic trends, political ideologies, societal values and macro-economic patterns (e.g. recessions, global oil prices). The socio-technical landscape also refers to rapid historical shocks and events (e.g. the Chernobyl explosions) that put pressure on existing regimes and create windows of opportunity for radical innovations [16].

Figure 3. The multi-level perspective (MLP) as a middle-range framework for analyzing socio-technical transitions to sustainability (adapted from Geels [1]). The MLP framework helps to analyze the barriers regarding the introduction and diffusion of sustainable technologies and explains the drivers for the breakthrough of innovations. It distinguishes three different levels: the niches (micro-level), sociotechnical regime (meso-level) and sociotechnical landscape (macro-level). The sociotechnical regime consists of three interlinked dimensions [20]: a) network of actors and social groups, b) formal, normative and cognitive rules, and c) material and technical elements.

The interaction between these levels is complex, dynamic and non-linear. According to this model, the transformation of regimes (first level: AC energy regime) starts in early niche markets. However, this rarely happens in a linear or directed way. Instead, radical innovations might come up spontaneously at a certain time and under specific conditions and actors’ constellation, which form the required social network. Niches do not develop independently from regimes and landscapes but are influenced by expectations, networks and power structures. Nevertheless, niches can challenge the regime by new emerging technologies or ideas that might promise improvements or progress in regime (infra-)structures. Due to vested interests and other stabilizing factors acting as barriers for innovations, novelties often remain in the niche for a long time until a window of opportunity opens up, which provides a breakthrough of the innovation at regime level. Breakthroughs can be triggered by changes at landscape level (e.g. through new regulatory measures or shifts in consumer preferences), which challenge regimes to open up windows of opportunities. If a novelty has reached the regime level it would create a new competition with regime structures via markets and infrastructures leading to a new configuration of the regime and to adjustments at various regime levels and processes. Having
won the competition with regime structures the innovation can, over time, also influence the beliefs, traditions and constitutions at landscape level. [20] In a nutshell, it is a complex interplay between the landscape and the niche level, which opens up opportunities at regime level for novelties to become influential, which at the long term can facilitate transition.

2.1.2 Transition Management

According to the MLP model, managing transitions towards sustainability is very difficult and for a single actor even impossible to pursue because of the interdependence between multiple actors and the role of autonomous developments in the socio-technical landscape [16]. Transition Management (TM) attempts to formulate guidelines taking into account contingencies created by multi-level developments and aim to facilitate multi-actor processes in the so-called arenas (Kemp and Loorbach, 2006). Regarded as a governance tool rather than a theory on transition, TM obviously has a stronger focus on societal actors such as governments, business, scientists, non-governmental organizations (NGOs) and intermediary organizations. Based on system theory, the TM approach assumes that these actors create formal and informal networks because of partially joint interests and the willingness to temporarily share certain resources in order to work for shared objectives [22].

The process of transition management is captured in a transition management cycle (see [22]) are:

1) Structure the problem in question and establish and organize the transition arena.
2) Develop a transition agenda, images of sustainability and derive the necessary transition paths.
3) Mobilize actors and establish and carry out transition experiments
4) Monitor, evaluate and learn lessons from the transition experiments, leading to adjustments in the vision, agenda and coalitions

Figure 4. The transition management cycle [22]

It can be seen that TM process does not reflect traditional planning strategies that see strategy formation as a formal, prescriptive process. Rather transition strategies should be seen as what Mintzberg et al. [23] call learning strategies. Learning strategies have an emergent rather than a deliberate character. In this context, determining one’s strategy becomes a continuous process of learning-by-doing. It is essential to maneuver strategically according to the historical and context conditions of an innovation journey. History refers to the past of a project and the innovation context to the wider developments in relevant regimes and the socio-technical landscape.

Raven described two patterns that can be used as strategies for dealing with the lockout of alternative innovations: niche accumulation and hybridization [16]. The first strategy in to apply the innovation in
different niche markets and improve and build up momentum through a process of niche accumulation. The second strategy is to start more closely to the existing regime and opt for a radical transformation through a process of hybridization. For the DC case, both patterns co-exist. The DC micro grid is added to the existing AC electrical wiring forming a hybrid system and can be applied and tested in various markets.

2.2 Methodology
The methodology used to address the transition to DC micro grids is based on Design Thinking (DT). DT is a method for developing innovative solutions for complex problems, by deliberately incorporating the concerns, interests and values of humans into the design process [24]. Although initially applied in the field of design (software, industrial), DT has gained traction in business, leadership and management sectors, amongst others, in order to cope with increasing complexity and to be used as a driver for innovation and business success [25] [26]. DT differs from conventional engineering, scientific and managerial processes in the sense that it is a solution-based approach starting with a goal (a successful future for DC) instead of problem-based. It involves a series of divergent and convergent steps and relies on an interplay between analyzing and breaking the problem apart, and synthesizing ideas about how to realize a viable future for DC applications. While different versions to articulate the DT process may be described slightly different, the basic tenants remain essentially the same [25]. The main phases of the traditional DT process are briefly explained [27]:

**Discover:** In the first phase the goal is to fully understand the problem and research it through different means (interviews, market research, field tests, etc.).

**Define:** The definition phase is the phase during which findings from the discovery phase are interpreted into meaningful insights. The output of the phase is the definition of an opportunity on which designers can base ideas and come up with solutions.

**Develop:** Based on the output of the definition phase, the designer approaches the problem by diverging to generate solutions. Solutions could be models, methods and prototypes.

**Deliver:** The final phase is the delivery stage where the resulting product or service is finalized and launched in the relevant market. Finalization implies that the product or service has been tested and proved to work.

An overview of the methodology is depicted in Figure 5. The traditional DT process was adopted and adapted to reflect principles from the theoretical framework presented above:

1. **Discover**

The integration of DC micro grids in buildings requires a radical transition in the energy sector. The first step was to discover the “historical context” [16] of the DC innovation and the challenges regarding the transformation of the existing energy regime to the envisioned regime that includes DC micro grids. The transition to DC falls within the energy sector. In order to define the history of the innovation, literature was reviewed to provide a better understanding of the current situation in the energy sector. Information about challenges in the transition to DC was found from previous research on DC and interviews with members of the DC-Flexhouse project. The interview questions can be found in the Appendix.

2. **Define**

This phase defines the innovation context: the exogenous factors that influence and shape the future of the DC innovation, as well as the strengths of the DC innovation itself. The current overall energy transition is a multidimensional challenge [28]. Building upon the Multi-level Perspective and the TM
models, factors related to the socio-technical regime and landscape were identified. Literature review and market research was conducted to elaborate on these DC-influencing factors. The reason for defining the innovation context is to assess the market potential of DC in the built environment.

3. Develop

This step involves the generation of ideas to enable the transition to DC micro grids. According to innovation literature [29], there are three entities that drive the market potential of any innovation: the technology itself, the consumer who must adopt it and the company that designs it. By analyzing these three entities for the DC case and applying principles found in MLP theory, a framework towards the commercialization of DC in the built environment is proposed. Rather than offering a formal, prescriptive strategy, this framework gives insight about potential adopters of DC technology and value creation within the DC context.

4. Deliver

Drawing upon the outcome of the previous steps and input from potential adopters and facilitators, the final step is the development of an action plan for the transition to DC. The action plan cannot be tested as DT suggests since this PDEng project finishes before the end of the DC-Flexhouse project. However, DC-Flexhouse project partners can adopt this action plan to steer activities towards the envisioned future for DC applications. Furthermore, a business plan is developed and a portfolio of business models is provided. The business models examine various ways to generate value for involved actors. In order to validate the business case of DC for involved industries, this step also includes the investigation of the business case for a specific market segment: residential buildings.

The above described process is iterative, meaning that intermediate outcomes and findings were used as starting point to redefine the challenges and refine ideas and solutions. Instead of being a linear process, the methodology involves moving back and forth between the different steps.

![Methodology (adapted from DT, MLP and TM)](image)

*The business plan is not publicly available*
3. Structure of the report

The structure of the report follows the different phases of the methodology as presented in Chapter 2.2.

Chapter 5 provides an overview of the current situation in the energy sector and presents the challenges associated with the transition to DC micro grids in the built environment. The theoretical framework (see Figure 3) is used to evaluate the current status of DC development and barriers in the market introduction of the innovation.

Chapter 6 analyzes trends and development across the different levels of the Multi-level perspective framework (see Figure 9) in order to assess the future market potential of DC.

Chapter 7 presents the benefits of DC and potential application areas. DC technology is compared to AC in two levels: 1) DC versus AC, and 2) smart DC versus smart AC.

Chapter 8 sets a framework towards the realization of DC micro grids in buildings. This framework is built across the three entities that drive the market potential of innovations: the technology itself, the market, and the ecosystem of companies that have to join their forces in order to reach the market. The technology part gives insight into system integration and scalability by analyzing the DC-readiness of potential system components (appliances). Market refers to the customers that have to adopt DC applications. Therefore, this chapter conducts a market analysis and identifies potential early adopters based on the value proposition of DC and market needs. Regarding the third entity, the ecosystem of actors that have to co-innovate in order for the value proposition to reach the market, this chapter identifies the actors in the case of the DC innovation, and stresses the necessity of a business model that creates value for both the market and the ecosystem of companies.

Chapter 9 presents an action plan with key areas of attention for companies and organizations involved in the DC-Flexhouse project. This action plan is developed based on my personal observations and guidelines suggested by innovation and transition management literature.

Finally, Chapter 10 describes the conclusions of this project and recommendations for further research.
4. DC innovation history

4.1 The energy landscape

Currently the energy sector is in a phase of renewable transition triggered by concerns about growing energy demand in relation to security of supply, energy costs and environmental issues. Government entities and other stakeholders work together to establish a long-term energy vision and successfully implement energy efficiency and renewable energy solutions. The goal is to reduce dependence on fossil fuels and secure a clean energy environment. The European Union has set its target for a 20% cut in greenhouse gas emissions, 20% share of renewables and 20% improvement in efficiency. It is expected that a large part of the renewable energy will be produced from decentralized sources [30], while the ongoing electrification is expected to lead to an increase in demand. In the near future, the grid must be able to cope with large amounts of decentralized energy production and the increasing electricity demand.

Today’s grids are predominantly based on large central power stations connected to high voltage transmission systems which, in turn, supply power to medium and low voltage local distribution systems. The overall picture is still that of one direction power flow from the power stations via the transmission and distribution systems to the final consumer. There is little or no consumer participation and no end-to-end communication. Renewable generation technologies have to be introduced into existing transmission and distribution networks, which were not initially designed to incorporate these kinds of technologies in the scale that is needed today. With the increasing integration of distributed generation (DG), the distribution grids are becoming active and will have to accommodate bi-directional power flows. [31]

These new forms of generation have different characteristics from traditional plants. Some of them, such as solar and wind energy, also exhibit greater intermittency. If EU energy policy continues to promote the increased use of DG there is an urgent need to transform Europe’s grids to allow for the larger scale deployment of these new technologies. The current structure of the energy infrastructure will not satisfy future needs: meeting the technical demands for transport capacity and reserve power will become increasingly costly as electricity demand increases and the share of intermittent DG grows. Distributed generation can have a material impact on local grids, causing reverse power flows, variation of local grid voltages and other technical parameters necessary for secure operation. The intermittent nature of sustainable energy sources will lead to a loss of system flexibility in terms of generation control and balancing potential. Effective and economic solutions have to be developed in order to secure a stable, sustainable and reliable supply of electricity.

Buildings can be part of the solution to these challenges, as they can offer flexibility in energy consumption and/or production. Flexibility refers to the capacity to increase or decrease the load in a certain time frame [32]. Indeed buildings are becoming an integrated part of the energy infrastructure, supplying energy produced by renewable energy sources, mainly photovoltaics. By applying Demand Response (DR) or Demand Side Management (DSM) programs, flexibility in energy consumption can be used to shift load in time. End-users adjust their consumption patterns in response to certain incentives that are usually financial. For example, DSM can be used to match demand to renewable

---

6 Demand response refers to programs designed to encourage end-users to make short-term reductions in energy demand in response to price signals from the electricity hourly market, or a trigger initiated by the grid operator. The goal is peak shaving and valley filling of the consumption pattern (measured in kW reduced). Demand Side Management programs encourage end users to be more energy efficient (measures include retrofits, building automation upgrades, etc.). The value of DSM is measured in kWh. Although DR and DSM are not interchangeable, they can complement each other. It can be said that DR is a subset of DSM.
generation or to reduce peak loads. The integration of storage is also being explored as a solution to minimize investments in grid reinforcement [33].

This integration of buildings in the energy system and the requirement to interact with other stakeholders necessitate the upgrade of the energy infrastructure to enable bi-directional power and information flow. The energy transition as well as the technological progress drive the increasing integration of information and communication technologies (ICT) and hence the transformation towards the so-called “smart grid”.

4.2 LVDC as a solution for energy and societal challenges
As explained in the previous Chapter, the importance of DC-based applications such as photovoltaic systems, storage and electromobility is growing as a result of the change in energy policy. At the same time, the rising demand for computing power is increasing the need for DC in electronic devices such as computers, servers, laptops, smartphones and tablets. LED technology that offers a more energy-efficient solution for lighting again works internally with DC power. By distributing DC power to DC loads instead of converting it to AC along the way, it is possible to avoid substantial energy losses that occur every time electricity is converted.

Furthermore, DC gives the capability of integrated digital control. The DC micro-grid that is being designed within the framework of the DC-Flexhouse project offers a smart grid solution. It enables flexibility in energy consumption offering capabilities for congestion management and supply and demand balancing.

In this context, it can be seen that low voltage DC is an alternative technological solution for distributing green energy in a safe and efficient manner.

4.3 Challenges in the transition to DC
Although DC contributes to a more sustainable world, the implementation of DC micro grids and the respective commercialization of LVDC products face both technology- and market-related challenges. Based on input from interviews with DC-Flexhouse members which represent various industries (manufacturers, designers, installers) and literature review, the following challenges are identified:

Table 1. Challenges in the transition to DC micro grids in the built environment

<table>
<thead>
<tr>
<th>Technology-related challenges</th>
<th>Market-related challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Technology Readiness Level (TRL)/need to experiment in isolated grids (laboratories/living labs/private grids)</td>
<td>No identified need, dominance of AC products and appliances</td>
</tr>
<tr>
<td>DC power poses different safety requirements in insulation and arquenching due to the nature of DC power</td>
<td>Resistance to change from an established regime (AC energy infrastructure)</td>
</tr>
<tr>
<td>Existing building codes and standards are specific to AC power and require amendments for wider application of DC</td>
<td>Actors from the industry do not see the advantage</td>
</tr>
<tr>
<td>Engineers and technicians are not trained in DC systems, resulting in inflated design and installation costs of these systems</td>
<td>Residential energy consumers are not interested in energy-related renovations</td>
</tr>
<tr>
<td>Devices are designed for AC markets/DC power input requirements need to be standardized, some of the devices need to be completely re-engineered to work with DC power</td>
<td>High investment risk</td>
</tr>
<tr>
<td></td>
<td>Prohibitive cost in the beginning</td>
</tr>
<tr>
<td></td>
<td>Uncertainty in business model innovation (from the supply side)</td>
</tr>
<tr>
<td>Unfamiliarity with DC</td>
<td>Uncertainty about effectiveness and value</td>
</tr>
</tbody>
</table>

While DC is already being exploited for the supply of electricity generated by distributed sources in developing countries, such as India and Africa, the business case in developed countries remains questionable. Cost uncertainties, limited creativity and cognitive ability to innovate by the side of the industry [34], the well-established AC energy infrastructure and a lifetime of producing and using AC devices are the main factors that are expected to deter or delay the adoption of DC innovation. Potential customers will see no value in a DC micro grid if it causes them hassle to find DC-ready products, and in turn manufacturers will have no interest in producing DC-ready products if they do not see a market.

Furthermore, people do not understand the difference between AC and DC, and are not able to experience or understand its value offering. In particular for radical innovations, conventional market research techniques such as customer surveys are not sufficient, because customers often have difficulty expressing needs for technologies that are not yet existing or fully developed [16]. Therefore, it can be said that DC faces resistance by both the demand and the supply side. In addition, changing regulations and energy policies increase the uncertainty regarding investments in sustainable renovations, such as PVs.

Figure 6. Overview of the DC innovation from a Multi-level perspective. The right column shows the barriers categorized across the dimensions of the current energy infrastructure.
The challenge to the introduction of DC innovation can be stated as follows:

The market potential of DC is debatable due to the established AC energy infrastructure, cost uncertainties, innovation risk, people’s resistance to change, ignorance regarding its value proposition and function, and changing regulations and legislation.

5. Can DC challenge the existing AC energy infrastructure?

According to transition theory and examples from other sustainability projects (e.g. photovoltaic technology [35]), it is most likely that DC application will initially enter niche markets and/or protective technological niches before penetrating the mainstream market. This Chapter discusses how the DC innovation can potentially challenge the existing energy regime in the future. The adoption of DC micro grids might be facilitated through trends and changes on the levels of socio-technical landscape, regime and niches. Therefore, factors and trends across the various dimensions and levels of the MLP model are identified (Figure 9).

Socio-technical landscape

Increase in DC loads: From the consumers’ point of view, an increase in the use of DC is experienced. Anything that uses transistors actually relies on DC such as laptops, PCs, flat-screen TVs, smartphones, etc. Such digital consumer devices account for up to a fifth of total power consumption today, according to Greg Reed, director of the Power & Energy Initiative at the University of Pittsburgh [36]. Within the next 20 years we could definitely see as much as 50% of our total loads be made up of DC consumption. In the Netherlands, ICT-devices account for approximately 14% of electricity use of Dutch households. This figure will continue to rise as the energy use for these devices grows at 7% a year in the Netherlands. There are no signs that this will slow down as the use of electronic gadgets at home grows rapidly [7]. Another factor that will increase DC consumption is the ongoing electrification of mobility (integration of Electric Vehicles (EVs) into the grid). EVs charge on direct current and require substantial amounts of power.

DC grids in developing countries: DC applications have already emerged in niche markets mainly in developing countries. Currently, 1.2 billion people worldwide do not have access to electricity. Decentralized energy systems based on renewables are exploited in order to benefit from access to electricity supply. In these cases, the use of DC is easier, simpler and more cost-effective compared to AC power. Projects are already implemented to develop DC distribution grids where energy is exchanged between households in order to maintain the balance between supply and demand [13]. Manufacturers of appliances see a new market there. To cover this demand, they are investing in developing appliances that are DC-compatible. Therefore, it can be expected that in the future the availability of DC appliances will increase in developed countries as well.

Socio-technical regime

Standardization in LVDC applications: The commercialization of DC highly depends on the existence of standards for LVDC applications that the industry can use to design and produce DC devices. Currently there is no standard for LVDC installations. However, the benefits of DC have been recognized by standardization bodies. The International Electrotechnical Commission (IEC), the international standards and conformity assessment body for all electrical, electronic and related technologies, has established a System Evaluation Group (SEG 4) to sort out the gap of standardization in the field of LVDC. The SEG 4 is evaluating the usage of LVDC in different integration environments in developed and developing economies with the objective to enhance energy efficiency and to develop new ways to utilize LVDC power.
On a national level, the Netherlands Standardization Institute (NEN) is the instrument that supports the standardization process in the Netherlands and works closely with IEC. NEN is also working on the respective standard for Low Voltage electrical installations (NEN NEC64). NEN has established a platform for interoperability and standardization in the field of smart grids, and NEN 64 Committee is part of this platform.

The German association for electrical, electronic and information technologies has already published the German Standardization Roadmap for LVDC [37]. According to this Roadmap, the market growth is currently difficult to gauge because only niche applications have emerged as yet. However, a significant market increase is to be expected in the coming years, especially because of the increase in DC loads and penetration of renewables.

**Regulations for improved energy efficiency:** The European Union has set its target for a 20% cut in greenhouse gas emissions, 20% share of renewables and 20% improvement in efficiency as a result of concerns about growing energy demand in relation to security of supply, energy costs and environmental issues. Government policies also focus on cutting the energy consumption in the built environment because buildings account for approximately 30% of total energy use. The “Nationaal Plan voor het bevorderen van bijna-energieneutrale gebouwen in Nederland” is the Dutch policy for nearly-zero energy buildings. According to this policy, from 2020 all new buildings have to be nearly energy neutral (BENG regulation), while for public buildings this applies from the beginning of 2019. The criteria for nearly-zero energy buildings are shown in Table 2.

<table>
<thead>
<tr>
<th>Building type</th>
<th>Energy demand (kWh/m²/year)</th>
<th>Primary fossil energy (kWh/m²/year)</th>
<th>Share of renewable energy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>25</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Utility</td>
<td>50</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>Educational</td>
<td>50</td>
<td>60</td>
<td>50</td>
</tr>
<tr>
<td>Healthcare</td>
<td>65</td>
<td>120</td>
<td>50</td>
</tr>
</tbody>
</table>

The policy for highly energy-efficient existing buildings is still under development [38]. However, the Energy Performance Standard (EPN) that sets requirements for the energy efficiency applies for both new buildings and major renovations [39]. Although currently, there are is no specific policy for existing buildings determining energy performance as is the case for new buildings, it is certain that in the future the government will put pressure for existing buildings as well.

**Increase in PV penetration:** Solar technology started from niche markets and gained a larger market share in recent years, imposing changes in the energy regime mainly though policy support (feed-in tariffs (FiTs), net metering, subsidies for R&D). The Dutch PV market is currently on the rise and it is
expected to keep growing as a result of the government’s push to achieve its renewable energy targets by 2020 and the projected drastic reduction of solar technology. The total installed capacity was 722 MW [40] in 2013 and the PV sector’s goal is to increase to 4 to 8 GWp [12]. Again, by distributing the DC power generated by the PV systems to DC loads instead of converting it to AC and then again to DC, substantial energy savings can be achieved.

Table 3. PV sector’s goals for installed capacity in the Netherlands

<table>
<thead>
<tr>
<th></th>
<th>2013</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV installed capacity</td>
<td>722 MW</td>
<td>4-8 GW</td>
</tr>
<tr>
<td>Number of households (in thousands)</td>
<td>80</td>
<td>450 - 900</td>
</tr>
<tr>
<td>Share of total electricity consumption</td>
<td>3-6%</td>
<td></td>
</tr>
<tr>
<td>Share of overall target for renewable electricity</td>
<td>10%</td>
<td></td>
</tr>
</tbody>
</table>

**The USB-C standard:** The USB-Type C is the latest USB development. With the continued success of the USB interface, there exists a need to adapt USB technology to serve newer computing platforms and devices as they trend toward smaller, thinner and lighter form-factors. Many of these newer platforms and devices are reaching a point where existing USB receptacles and plugs are inhibiting innovation, especially given the relatively large size and internal volume constraints of the Standard-A and Standard-B versions of USB connectors [41].

The USB-C standard combines power delivery up to 100W and high speed data transfer (up to 10Gbps). The increase of the power capacity allows larger devices such as laptops to use a USB connector for power supply. The USB-C was developed by the USB Implementers Forum that counts over 700 companies in its membership, including Apple, Dell, HP, Intel, Microsoft, and Samsung. This is important, because it's more likely to be adopted by the majority of electronics manufacturers. According to Jeff Ravencraft, president and COO of the USB Implementers Forum, “The rollout of USB-C is going great, above and beyond their wildest dreams” and “This is the fastest transition they have seen in 15 years or more” [42]. Apple has already adopted USB-C for its latest MacBook.

The USB-C standard facilitates the design of DC devices, because it is the most common plug used for electronics and works with DC power.

** Niches**

**Need for storage:** In on-grid areas, Electrical Energy Storage (EES) or battery storage is a technology that is expected to solve problems that are associated with the use of large amounts of renewable energy, such as excessive power fluctuation, undependable power supply [43], voltage rise at the point of common coupling (PCC) and overloading in cabling and transformers due to reverse power flow [44]. Additionally, EES is a source of power system flexibility that increases the alignment between renewable energy generation and demand, contributing to better exploitation of renewables [45].

Although from a technological point of view, battery storage is mature, it has not reached the mainstream market yet. The main obstacles are performance and safety issues, regulatory barriers and social acceptance. However, the market outlook appears to be positive [46]. More specifically, solar PV and battery storage at the household level is driven by government support, concerns over electricity supply in areas with weak grid and economic trends. These include decreasing costs of small-scale battery systems, falling FiTs and rising retail electricity prices [46].

In can be clearly seen that government support is a key driver for the mass adoption of battery storage as is for the case of PV adoption by the mainstream market. According to [46], cost reductions are not the only parameter that will determine the future deployment levels of different battery storage
systems. Instead, the deployment and value of battery storage technologies for renewable integration will depend on the creation of an appropriate ecosystem with significant interplay between policy, regulation, business models, and consumers.

**Need for smart grids:** As explained in Chapter 4.1, the energy sector is in a phase of transition. The large amounts of intermittent decentralized energy generation and the increasing energy demand will lead to a loss of system flexibility in terms of generation control and balancing potential [30]. These challenges drive the evolution of the next generation smart grids. Soon actors in the energy sector will have to invest in upgrading the existing electrical infrastructure in order to tackle these issues.

The EU has been developing policies and funding schemes to support the energy transition since 2006. The Netherlands, in particular, also undertakes initiatives for developing intelligent power systems by subsidizing R&D and demonstration projects. The figure below illustrates a timeline as developed by the Top Sector Energy for smart grid development [47]. According to this timeline, large scale demonstration projects are currently being conducted.

![Figure 8. Smart grids development timeline for the Netherlands](image)

Although the necessity of smart grids is widely recognized, smart grid applications have not achieved change in the existing energy regime yet. Large scale implementation of smart grid concepts is challenged by diverging technological developments, cost uncertainties, changing markets and the lack of interoperability and general design- and technology frameworks [11] [48] [49]. Furthermore, lack of awareness from both the professionals’ and the consumers’ side is also slowing down the implementation of smart grids. The absence of a robust empirical evidence regarding the performance and economics of new technologies and tariff design on a system wide basis lead to increased risk in necessary investments and therefore hesitation. Social acceptance is also an issue, because the integration of Information and Communication (ICT) on top of the power grid and emerging smart grid applications (Demand Side Management) rise concerns related to cyber security and data privacy.

**Niche markets in developed countries**

In developed countries, data centers constitute a niche market. A pilot project conducted by ABB at the data center of the ITC service provider Green in Switzerland revealed a cut of energy consumption by 10% [50]. Facebook also adopted a DC architecture in its Prineville, Ore., data center [51].
Figure 9. The future potential of DC innovation assessed according to the MLP framework. The PV market has boomed over the last years mainly due to policy support (net-metering scheme). Battery storage and EVs (DC technologies) are currently niche markets, however the market outlook is positive. Again, policy support is expected to play a significant role. The right column in addition to the barriers shows the opportunities that arise within the developments in the broader energy landscape. It can be argued that although currently there is no explicit market need for DC applications, DC fits within the overall developments in the energy sector.

The analysis of the current situation and future trends reveals that although the market potential of DC is highly debatable at this moment, DC innovation fits within the overall energy transition and can have a market potential in the future if managed properly.
6. Benefits of DC and application areas
This chapter provides a more detailed description of the benefits of using DC instead of AC and presents potential application areas in the built environment.

6.1 Advantage of DC over AC
DC technology can be compared to AC in two levels: 1) DC grids to AC grids, and 2) DC smart grids to AC smart grids.

6.1.1 DC versus AC
The benefits of using DC instead of AC include:

- **Reduction in primary energy consumption**: Distributing DC power to DC loads instead of converting it to AC along the way can lead to substantial energy savings. The figure below shows the differences in the architecture between a conventional AC and a DC grid and respective converter efficiencies for a household with photovoltaics.

```
<table>
<thead>
<tr>
<th>Power system component</th>
<th>Efficiency (%)</th>
<th>Efficiency in literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV inverter</td>
<td>95</td>
<td>[52]</td>
</tr>
<tr>
<td>PV DC/DC controller</td>
<td>98</td>
<td>[53]</td>
</tr>
<tr>
<td>AC/DC converter</td>
<td>87 - 93</td>
<td>87: [54], 93: [53]</td>
</tr>
<tr>
<td>DC/DC converter</td>
<td>90 - 95</td>
<td>90: [55], 95: [56]</td>
</tr>
</tbody>
</table>
```

![Figure 10. AC versus DC building distribution with PV system and power system conversion efficiencies](image)

The overall efficiency of the power path is the product of the efficiencies of the PV converter and the power converter of loads (Figure 10). Comparing the high efficiency systems in both cases, energy savings can be around 5%.

Additional energy savings are achieved because of the lack of reactive power which in an AC grid create additional transmission losses.

- **Grid power quality**: The grid quality can be improved due to the elimination of AC harmonic oscillations.

- **Higher power transmission with identical wire cross-sections**: A conductor that connects two nodes in a network, which was previously effectively operated with an alternating voltage of 400 V, can reduce its cross-section by a factor of 0.867 using a DC voltage of 400 V DC [37].

- **Easier integration of alternative energy sources**: Renewable energy technologies such as PV and storage systems such as batteries also work on DC power. As is the case in the current situation,
in DC grids there is also need for power converters in order to connect these technologies to the grid, however DC/DC converters are more efficient and smaller because of the removal of the rectification and power factor correction stages (PFC). The existence of DC distribution grids will facilitate the integration of these components into the grid.

- **Fewer components and therefore lower capital costs:** Again the elimination of conversion steps leads to the reduction of necessary components which subsequently leads to the decrease of required capital cost. For example, for the integration of PV systems only a Maximum Power Point Tracker (MPPT) is necessary in the DC-world instead of both a solar inverter and a MPPT as is the case in the current situation.

- **Longer life expectancy of appliances:** AC to DC converters include electrolytic capacitors which have a low lifespan. In DC converters do not need these elements leading to the extension of the lifespan of appliances [57].

- **Convenience and aesthetics:** The distribution of DC power to DC allows users to get rid of all various adapters they use to power their electronic devices.

- **Reduction of weight and space requirements:** In the DC-world, users will not have to carry heavy laptop adapters, while DC enables space savings because of fewer or smaller components.

### 6.1.2 Smart DC versus smart AC

The benefits of the implementation of smart grids in the DC-world compared to the AC-world are:

- **Increased robustness to failure**
- **Simpler implementation**
- **Secured data privacy**

The smart grid describes the needed evolution of the energy infrastructure as a result of the increasing electricity demand and the integration of decentralized energy generation. The intermittent nature of sustainable energy sources will eventually lead to a loss of system flexibility in terms of generation control and balancing potential. Various smart grid applications are currently being explored in order to ensure reliability of supply at acceptable costs.

Demand Response (DR) and Demand Side Management (DSM) are promising smart grid applications that require the involvement of energy consumers and are already being explored. Buildings can be a part of the solution to the challenges the energy sector faces as they can offer flexibility in energy consumption and/or production. By enabling flexibility, buildings can provide balancing services to the electricity market and congestion management services in the distribution system. DSM provides financial incentives in order to encourage consumers to shift electricity consumption during periods of high demand to off-peak periods or during periods of excess renewable energy generation.

**Description of smart grid implementation in the current situation**

In the AC-world, smart grid applications require a complex network of networks, comprising both power and communication infrastructures and intelligent electronic devices. To make the existing electric grid intelligent there is need for an additional ICT layer on top of the power infrastructure. The smart grid architecture is depicted in Figure 11 [58]. In general, a smart grid comprises: (1) a power system layer, which refers to power generation, transmission, distribution and customer systems; (2) a power control layer, which enables smart grid monitoring, control, and management functions; (3) a communication layer, which allows two-way communications in a smart grid environment; (4) a security layer, which provides data confidentiality, integrity, authentication and availability; and (5) an
application layer, which delivers various smart grid applications to customers and utilities based on an existing information infrastructure [58].

<table>
<thead>
<tr>
<th>Smart Metering and Grid Applications</th>
<th>Customer Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authentication, Access Control, Integrity Protection, Encryption, Privacy</td>
<td></td>
</tr>
<tr>
<td>Cellular, WiMAX, Fiber Optic</td>
<td>PLC, DSL, Coaxial Cable, RF Mesh</td>
</tr>
<tr>
<td>WAN</td>
<td>NAN/FAN</td>
</tr>
<tr>
<td>PMUs</td>
<td>Reclusers</td>
</tr>
<tr>
<td>Power Transmission/Generation</td>
<td>Power Distribution</td>
</tr>
</tbody>
</table>

Figure 11. The system multi-layer architecture of the smart grid [58]

The communication layer is one of the most critical elements that enables smart grid applications including DR and DSM. In the smart grid environment, a communication network can be represented by a hierarchical multi-layer architecture. Classified by data rate and coverage range, this architecture comprises [58]:

- Customer premises area network, i.e., Home Area Network (HAN)/Building Area Network (BAN)/Industrial Area Network (IAN)
- Neighborhood Area Networks (NAN)/Field Area Network (FAN)
- Wide Area Network (WAN)

Within the scope of this study, the focus is on the building level and the interaction with the grid in terms of NAN/FAN applications such as DR.

Premises network applications

A premises network, i.e. HAN/BAN/IAN, is at the customer end of the network architecture. It supports communications among appliances, electric vehicles, and other electric equipment such as renewables and storage at customer premises. The HAN applications include home automation, controlling and managing loads and providing total electricity consumption and costs.
The premises network is connected to other smart grid actors, e.g. grid operators or service providers, via a smart meter or an Internet gateway. This is the interface between a building and the grid operator. This interface enables the implementation of NAN/FAN applications in buildings, such as prepaid services, real-time pricing and control, load management and DR.

**Neighborhood Area Network applications**

A NAN supports information flow between WAN and a HAN. Once the HAN devices communicate data to the smart meter, this information should be carried to a data concentrator/aggregation point, often is a substation, a pole-mounted device, or a communication tower [59]. NAN enables data collection from customers in a neighborhood for transmission to a grid utility company. NAN/FAN is connected to WAN via a backhaul network, where data from many NAN/FAN are aggregated and transported between NAN/FAN and WAN.

There is a wide variety of technologies and respective standards/protocols that can be harnessed for each level in the communication hierarchy. On the premises level, customers can choose from wired, wireless or hybrid (combining both wired and wireless). Wireless technologies on the premises level are ZigBee, WiFi, Z-Wave, Bluetooth, while wired are Power Line Communications (PLC), Ethernet and KNX. PLC such as HomePlug uses existing electrical wiring in the house/building to carry data. Although there is no general consensus yet on a standard, ZigBee, followed by HomePlug, appears to be promising technologies for smart grid applications [59]. KNX is also an open, worldwide standard that is supported by more than 300 vendors.

On the neighborhood level, smart grid applications can be implemented over ZigBee mesh networks, WiFi mesh networks, PLC, as well as long distance wired and wireless technologies, such as WiMAX, Cellular, Digital Subscriber Line (DSL) and Coaxial Cable.

Apart from the communication layer, the control approach is also critical to enable flexibility in energy consumption. The PowerMatcher principle and priority-based control are two promising control concepts for balancing supply and demand in the current situation.

It can be concluded that the implementation of smart grid concepts in the AC-world is complex and challenging. The safe operation of the grid in the current situation heavily relies on the integration of ICT components on top of the power infrastructure, the communication among these components and real time control. Congestion management on the distribution level is implemented with current sensors and safe operation depends on the communication and data exchange among these sensors. Therefore, the operation of the system is vulnerable if communication fails. Moreover, existing smart grid concepts require that energy consumers will share information regarding their electricity use; a fact that raises concerns about data privacy and as a consequence social resistance.

**Description of smart grid implementation in the DC-world**

In the DC-world, the implementation of smart grids in terms of supply demand balancing and congestion management is simpler. The in-house DC installation that is being designed within the framework of the DC-Flexhouse project will be smart by its nature, securing reliable and safe operation without the need of additional communication equipment. It comes equipped with an energy management system to monitor in-house energy usage and generation. The system can activate or shut down itself and connected devices, in order to manage sources such as PVs and the grid connection.

The concept is that load management on building level contributes to congestion management on distribution level. Load management is based on voltage levels (voltage droop control) according to
the DC\textsuperscript{2} voltage protocol which is currently being developed by the company Direct Current BV. Devices are given priority in terms of the need to consume energy. High priority devices will be switched on when needed and lower priority appliances will be activated only when power supply is sufficient to switch on appliances with high priority. The priority is set by the protocol, however the user has also the freedom to change it. The logic of the control is based on “if statements”\textsuperscript{7}:

- if $V_{bus} > V_{limit,i}$ → consume or store ($S > D$)
- if $V_{bus} < V_{limit,i}$ → minimize consumption based on priority ($S < D$)

where:

- $V_{bus}$ = voltage at the DC bus,
- $V_{limit,i}$ = priority voltage given to devices,
- $S$ = supply (can be only supply by the PV system or available supply on district level),
- $D$ = demand.

When the energy that is locally generated by the PV is not consumed by the building, the voltage level on the DC bus increases due to reversal power flow. In this case, loads start consuming or energy is stored and the bus voltage settles back to the nominal operating voltage. On the contrary, when the demand is higher than the supply, it causes a decrease in the bus voltage. Loads are disconnected and only priority loads are supplied with electricity. The bus voltage again increases to its nominal level.

The target is that DC devices are designed based on this protocol. Therefore, even if communication fails the system remains always balanced. Additionally, controllers and sensors are integrated in the devices and are not added as an additional layer (AC-world) which again increases the robustness and reliability of the system.

Advanced smart grid concepts such as predictive and priority-based control require communication among the devices and software applications as is the case in the AC-world. However, supply and demand balancing and congestion management do not rely on these applications. They are secured through the way new DC devices will be designed (by adopting the DC\textsuperscript{2} voltage protocol).

In the envisioned DC system, the electrical wiring is used for communication purposes. The use of the physical infrastructure for data communication is favored over wireless communication from a privacy point of view. Listening in on physical infrastructure is more difficult than listening in on wireless communication [60]. In this respect, it could be argued that DC offers security and data privacy.

\textsuperscript{7} More information cannot be disclosed due to confidentiality reasons.
6.2 The variety of application areas in the LVDC markets
This Chapter aggregates different technologies in the built environment that can be realized with DC. The table below presents these technologies, respective advantages and possible application areas.

Table 4. Application of DC in buildings

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>ADVANTAGES</th>
<th>APPLICATION AREAS</th>
</tr>
</thead>
</table>
| LED lighting                        | • Reduction of energy consumption  
• Reduction of space requirements  
• Reduction of equipment weight  
• Flexibility in the placement of components  
• Integrated digital control (e.g. PoE) | • Office  
• Commercial building  
• Data centers/ICT  
• Residential building  
• Educational buildings  
• Industrial building  
• Healthcare building/Hospital  
• Outdoor lighting |
| Power supply for electronic devices | • Reduction of energy consumption  
• Reduction of space requirement  
• Reduction of equipment weight  
• Higher power transmission capability with identical cross-sections  
• Integrated digital control (potential data transfer over wiring/USB-C standard) | • Office  
• Commercial building  
• Data center/ICT  
• Residential building  
• Healthcare building/Hospital  
• Educational buildings |
| Integration of renewable energy sources | • Reduction of conversion losses  
• Optimized use of renewable energy  
• Reduction of space requirement  
• Reduction of equipment weight | • Office  
• Commercial building  
• Data center/ICT  
• Residential building  
• Educational buildings  
• Healthcare building/Hospital |
| Battery storage systems (e.g. UPS systems) | • Reduction of conversion losses | • Office  
• Commercial building  
• Data center/ICT  
• Residential building  
• Educational buildings  
• Healthcare building/Hospital  
• Industrial building |
| Distribution of DC & smart grids    | • Higher power transmission with identical wire cross-sections (or same power transmission capacity for smaller wire cross-sections)  
• High penetration rate of intelligent hardware thanks to electronic transducer technology  
• Replacement of existing AC low voltage networks and parts of medium voltage networks through LVDC reduces the overall life cycle cost of energy distribution and allows smart grid services to be offered to all electricity market players | |
7. Framework towards DC in the built environment

The transition to DC as a radical innovation is expected to face resistance by both the market and the industry. The three entities that drive the market potential of the innovation are: the technology itself, the customer that must adopt it and the ecosystem of companies that have to join their forces in order to reach the market. By analyzing these three entities, this Chapter proposes a framework towards the realization of DC micro grids in buildings.

7.1 The technology

7.1.1 DC-readiness of devices

The commercialization of DC micro grids highly depends on the availability of DC products that end-users can purchase and use. There is no value of a DC micro grid if appliances that can be directly plugged in do not exist. The choice of a DC micro grid should not cause any inconvenience to the potential customer. It has to be easy for them to find DC-ready devices. Table 5 categorizes various appliances used in buildings in terms of DC-readiness, meaning how easy it is to be configured for DC power supply.

Table 5. DC-readiness of appliances

<table>
<thead>
<tr>
<th>Group</th>
<th>DC readiness</th>
<th>Appliances</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DC ready</td>
<td>Laptops, TVs, smartphones, ICT, batteries, kettles, ovens, water boiler, etc.</td>
</tr>
<tr>
<td>2</td>
<td>Needs adjustment to support variable speeds</td>
<td>Vacuum cleaners, blenders, washing machines, heat pumps, etc.</td>
</tr>
<tr>
<td>3</td>
<td>Will not work with DC</td>
<td>Fans, fridges, freezers, etc.</td>
</tr>
</tbody>
</table>

The first group includes computing, lighting and small heating appliances. These appliances work internally on DC and they are sold either with external power supplies intended to convert AC to DC or have an internal AC to DC converter. Heating appliances use electric resistances that work both on AC and DC with no problem. These products are designed for AC markets and could be easily used in a DC context if their DC power input requirements were standardized. Batteries and PVs are also DC technologies, however components that integrate them to the grid have still to be developed for connection to a DC grid and for the chosen voltage level (350 V).

With the DC micro grid envisioned in the DC-Flexhouse project, electronic devices can be directly plugged into the USB-C wall sockets without the need of adapters. The adapters is integrated in the wall socket. Therefore, the availability of DC-ready electronics depends on the adoption of the USB-C standard by manufacturers and in turn the adoption of these devices by end users. The USB-C connector was developed by the USB Implementers Forum which counts over 700 companies in its membership, including Apple, Dell, HP, Intel, Microsoft, and Samsung. This is important, because it's more likely to be accepted by the majority of electronics manufacturers. Apple has already adopted USB-C for its latest MacBook. A list with products that come with a USB-C port is provided in the Appendix.

The second group consists of appliances that can directly work on DC, however, they need some modifications in order to be able to support variable speeds. The modifications improve the energy efficiency and the lifespan of the appliances, but currently they are at least a factor two more expensive [54]. Finally, the appliances in the last group will not work with DC mainly because they use an AC
motor. In these cases, the appliances have to be redesigned or the motor has to be replaced with a DC one.

In the context of smart grid applications, the real potential of DC lies in the availability of DC appliances that enable flexibility in energy consumption. Such appliances are shown in the table below and are categorized based on the type of flexibility they offer.

Table 6. Potential sources of flexibility in buildings and DC readiness

<table>
<thead>
<tr>
<th>Type of flexibility</th>
<th>Buffer</th>
<th>DC readiness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric buffering</td>
<td>Battery</td>
<td>DC-ready</td>
</tr>
<tr>
<td>Thermal storage</td>
<td>Heat storage for space heating</td>
<td>DC-ready</td>
</tr>
<tr>
<td></td>
<td>Heat storage for hot water</td>
<td>DC-ready</td>
</tr>
<tr>
<td>Shiftable loads</td>
<td>Washing machines</td>
<td>Need of adjustments</td>
</tr>
<tr>
<td></td>
<td>Dryers</td>
<td>Need of adjustments</td>
</tr>
<tr>
<td></td>
<td>Dish washers</td>
<td>Need of adjustments</td>
</tr>
<tr>
<td>Peak shavers(^8)</td>
<td>Refrigerators</td>
<td>Will not work</td>
</tr>
<tr>
<td></td>
<td>Freezers</td>
<td>Will not work</td>
</tr>
<tr>
<td></td>
<td>Stoves</td>
<td>DC-ready</td>
</tr>
<tr>
<td></td>
<td>Appliances with batteries</td>
<td>DC-ready</td>
</tr>
<tr>
<td></td>
<td>(laptops, smartphones, etc.)</td>
<td></td>
</tr>
</tbody>
</table>

The scalability of the DC grid in terms of the number of appliances it can integrate and the various functionalities it can serve depends on the availability of DC-ready appliances. In turn, the market for DC applications also depends on the availability of DC-ready appliances. According to experts' opinion, DC will not fully replace AC. Therefore, at this moment it can be assumed that buildings will be supplied by hybrid AC and DC power for AC and DC appliances respectively.

### Availability of DC products from niche markets in developing countries

There is a small availability of DC products mainly from off-grid niche markets. Mobile applications include road transportation, rail and marine. Stationary applications include primarily remote commercial applications (e.g. shelters for telecom equipment, meteorological monitoring) and off-grid residential. All of these products are designed to be integrated with lead-acid battery storage, which determines the three voltages (12V, 24V, 48V). They are frequently marketed for PV integration. Currently, there are DC appliances for three dominant electricity end-uses, namely cooling, lighting, and refrigeration, which together consume about 40% of total electricity in residential and commercial markets. There are also smaller DC appliances dominated by 12V fans, griddles, microwaves, blenders, heaters and hair dryers. More information on DC products can be found in [61].

### 7.1.2 System integration and scalability

The DC installation on the building level can integrate various components (appliances/devices). In the beginning of technology development, the DC installation can integrate components that already work internally on DC power. Early applications, therefore, can include PVs, battery storage, EVs, LED lighting and electronics, with various configurations such as only PVs and DC-ready loads (mainly for commercial applications) or PVs in combination with battery storage.

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\(^8\) Peak shavers are loads that can be given less electricity or be temporarily switched off without compromising their function or the user's comfort. These loads can be used for congestion management in the in-building installation. For example, peak shavers can be used when demand is bigger than the one the cable can handle.
At a later stage, the system can be scaled up to integrate components that need adjustments, either simple or complicated. The categorization of appliances regarding the DC readiness is presented above (see Table 5). The integration of heat pumps and water boilers is highly interesting. According to a study [7], electricity consumption for heating accounts for 15% of total electricity use for Dutch households (Figure 13). Therefore, by coupling heat pumps and water boilers to the DC installation, the building owner can benefit from the PV output and avoid utility costs.

Especially for residential applications there is need for storage and/or shiftable loads in order for the building owners to benefit from both the consumption of the energy produced by the PV installation (thus minimizing their electricity bill) and the energy savings due to the elimination of DC to AC to DC conversion steps. This is because in residential buildings there is a mismatch between renewable energy generation and building occupancy. In the absence of storage or shiftable loads, only the loads coincident with PV system output can benefit for direct DC power supply. Therefore, from an economic perspective, the DC installation will not be an attractive solution for the building owner.

![Figure 13. Electricity use by households in the Netherlands (source ING Bank [5])](image)

![Figure 14. Potential system components and scalability depending on DC-readiness](image)
7.2 The market

7.2.1 Market needs

The building market is subdivided in different segments depending on the use and type of the building. The main types are residential, commercial, educational and government buildings. As discussed in Chapter 1.1, DC technology could be applied in all these types of buildings with various configurations. However, the needs and perceived values, as well as the value proposition and economic feasibility of DC, are different for each market segment.

This Chapter performs an analysis of the needs of the stakeholders involved in the built environment in order to identify market segments where DC technology can fit. DC can have a big impact in markets where offered benefits and market needs intersect.

Building users are not the only stakeholder in the built environment. For example, today buildings play an active role in the overall energy transition; a fact that gets them involved in the energy sector. Furthermore, with regards to renovations, the building user is not always the party that finances the project, as is the case for commercial buildings and housing corporations. The key stakeholders in the built environment are presented in Figure 16. In order for DC to be a commercial success, it has to provide high value for all stakeholders.
Figure 16. Stakeholders in the built environment

Needs in the built environment

People spend on average 85-90% of their time inside buildings [62] [63]. For building users, comfort is one of the primary values a building should offer. Comfort is a complex emotional value influenced by, for example, spatial qualities, service provision and user interaction. The needs of stakeholders in various building types are as follows:

Residential buildings

The residential sector varies in terms of ownership. In the Netherlands, 55% are privately owned, 33% of households are owned by housing corporations and 12% by landlords.

Private households: The electricity costs for privately owned residential consumers constitute a small proportion of their electricity bill and, therefore, they are not interested in investing in renovations related to energy efficiency [64]. However, they do decide to invest in renovations and technologies based on emotional values, such as the positive experience they might gain.

Housing corporations: The rental housing market in the Netherlands is dominated by the regulated social housing segment. Social housing corporations (woningcorporaties) are non-profit organizations that have to act on a commercial basis, but are required to use their profits for the provision of good and affordable housing [65]. The Social Rented Sector Management Order (known by its Dutch abbreviation, BBSH), states that approved housing corporations have six duties:

- house those people who are not able to find an appropriate dwelling themselves,
- maintain decent-quality dwellings,
- consult with their tenants,
- run their financial affairs responsibly,
- contribute to livable neighborhoods, and finally,
- provide housing (but not care) for the elderly and handicapped.

A major change in the Dutch housing policy occurred in the 1990s, when most of the subsidies on housing construction were abandoned, and housing corporations became, after many years of deregulation, financially independent, although still subject to government supervision.

This development changed their business model. Housing corporations now have to finance themselves. In addition to earning revenues from rents, they raise funds through activities in the non-social housing sector (renting to people with higher income, construction and selling of homes) and can raise capital from selling dwellings which are recorded on their books at values far below market values. The government offers housing corporations various cost-reducing facilities, mainly through
the Guarantee Fund for Social Housing (*Waarborgfonds Sociale Woningbouw*, or WSW) with relatively low interest rate loans. Improved energy efficiency and zero on the meter are concepts explored as a strategy to raise capital for building renovations (see *Stroomversnelling* initiative). The business model in this case is as follows:

- The tenants pay rent and a fixed fee for electricity to the housing corporation
- The housing corporation uses revenues from electricity savings to pay back their investment in energy efficiency improvement measures. Investment is initially made through the Guarantee Fund for Social Housing.
- After investment is paid back, cost savings due to energy savings constitute an additional revenue stream for the housing corporation.

**Commercial buildings**

In the commercial market, energy costs could be substantial, depending on the type and use of the building. Measures to improve energy efficiency can be appealing when they guarantee a reduction in operating costs. Additionally, capital providers or real estate owners in this sector perceive also non-monetary aspects, such as reputation and green image, as valuable because these aspects increase the total value of ownership (TVO).

An overview of stakeholders’ needs and an indication of the expected value perception is shown in Figure 17. Benefits that can be offered by choosing DC and important factors that influence decisions for investments in buildings are rated in terms of relevance for the stakeholders.

![Figure 17](image)

Figure 17. Value perception of the different stakeholders in the built environment. The columns represent benefits offered by DC and factors that influence decision making for investments.

It can be concluded that perceived values are different in different markets and for different stakeholders. Depending on the type of building, the financier of projects and the building users can be different entities, as is the case for commercial buildings and housing corporations. For the financier
who is the key decision maker regarding investments, the total value of ownership is one of the most important aspects due to probable financial risks. The known concept of total cost of ownership (TCO) considers the total cost over ownership whereas the total value of ownership (TVO) also considers qualitative aspects such as contributions to image, reputation, property value and other benefits that influence the value of an investment. Apparently, financers in both commercial and rental housing corporations have a high regard for economic value and a reduction in operating expenses. The majority of private households is not currently concerned about electricity costs, however it has a high value perception of comfort. The local government focuses on social value, cohesion and land value.

Needs in the energy sector
The energy sector faces challenges regarding the reliability of supply and maintenance of energy at affordable costs. The electricity supply infrastructure is still that of one direction power flow from the central power stations via the transmission and distribution systems to the final consumers. The electricity grid is centrally controlled depending on the demand.

However, with the increasing integration of distributed generation (DG), the distribution grids are becoming active and will have to accommodate bi-directional power flows [66]. These new forms of DG such as solar and wind also exhibit great intermittency. In parallel, ongoing electrification is expected to contribute to an increase in demand [67]. The integration of distributed intermittent generation in conjunction with the increase in electricity demand will soon have a material impact on the grid (grid reinforcements) and challenge safe operation with potential congestion and imbalances leading to high costs and possibly to instability.

These complex challenges are driving the evolution of smart grid technologies. Actors in the energy sector are exploring solutions such as DSM and are trying to incentivize energy consumers to accept and engage in flexibility in their energy consumption. Using flexibility on the demand side, consumption can be reduced when supply is low or when there is congestion in the grid, or increase when there is excess generation. This way the demand side contributes to balance and capacity management leading to a potential reduction in operational costs and the need for investment in grid reinforcement.
7.2.2 Potential early adopters

Market introduction of DC technology falls within the technology push strategy. In the innovation literature, there is a distinction between technology push and market pull. Technology push is the process when research and development in new technologies drives the development of new products. These new products initially do not satisfy an identified user need. In contrast, innovation based upon market pull is developed by R&D in response to an identified market need (Figure 18). Partners in the DC-Flexhouse project design a technology that does not satisfy an identified user need at the moment. In order to transform this technology push to market pull and facilitate market development, DC-Flexhouse project partners should focus on market segments that are more likely to adopt DC innovation (early adopters).

According to research on customers’ psychology, many innovations fail because of a universal, but largely ignored, psychological bias: People irrationally overvalue benefits they currently possess relative to those they do not. Unless the gains from a new product far outweigh the losses from quitting the old one, consumers will not adopt it [29]. A lifetime of using AC products and the AC electrical infrastructure will lead to social resistance to change. To minimize consumer resistance, companies that have vested interest in promoting the transition to DC micro grids can:

- Target market segments that are willing to pay a higher price because of particular benefits they could gain from an innovation [16]: Potential benefits could be both monetary and non-monetary (e.g. reputation).
- Seek out the unendowed: focus on consumers who are not yet users of incumbent products
- Find believers: seek out consumers who prize the benefits they could gain from a new product or only lightly value those they would have to give up
- Be patient and let the market develop through pilot and demonstration projects: when it comes to sustainable innovations early niche markets might not exist (no individual is willing to invest in sustainability). In these cases, technological niches become operational through a series of protected test beds such as pilot and demonstration projects.

Building upon the above analysis, the following paragraphs suggest groups of potential early adopters by synthesizing trends (Chapter 5) and stakeholder needs (Chapter 7.2.1).

**Target markets where DC can have a big impact today**: The potential of DC for end users lies on the presence of DC loads. Currently, DC-ready devices are LED lights and electronics. Therefore, at the
moment DC can have a substantial impact in terms of energy savings in buildings with a high demand for lighting and computing power, such as offices and data centers. Data centers actually already constitute a niche market. Higher DC load translates to higher energy savings and in turn higher cost savings that increase the attractiveness of DC technology in financial terms for this market.

Another factor that determines the potential of DC is the level of coincidence with PV system output. The load in commercial and educational buildings coincides better with DC output from PV. Such buildings are occupied mainly during the hours that solar energy is produced. This again makes these two sectors better candidates for DC. PV output can be directly supplied to DC loads without the need of storage. It should be noted that it is more energy efficient to consume directly rather than store and consume afterwards.

In the case of residential buildings, loads have poorer coincidence with PV system output than commercial loads and are less predictable. In order to achieve the maximum benefit there is a need for storage and an energy management system (EMS). The integration of storage increases the required capital from the customer’s side. At the same time, the electricity bill for residential consumers constitutes a small proportion of their income and therefore they are not willing to invest in measures to improve energy efficiency [64].

A case study for residential buildings shows that in case of connection to the conventional AC distribution grid, DC is not an economically feasible solution because of the need of a bi-directional AC-DC converter (see Part B). It can be concluded, that more likely, if DC takes off in the residential sector for privately owned households, it will be as a spin-off of the commercial sector.

This might not be the case for housing corporations. Energy savings from a number of buildings could be a substantial revenue source for them. Indeed, housing corporations are already exploring ways to finance building renovations in order to meet energy performance standards. Energy savings achieved via renovations is a way to finance such projects as explained above. Housing corporations join forces with construction companies to develop nearly-zero energy buildings by exploiting the net metering policy. Tenants pay their energy bills to the housing corporation and the corporation uses this new cash flow to finance the renovation.

**Seek out the unendowed:** DC-Flexhouse project focuses on the renovation of existing buildings. However, new buildings, both commercial and residential could also be an early adopter, especially with the new BENG regulation that stipulates that all new buildings have to be nearly energy-neutral after 2020 (Chapter 0). In the case of new buildings, the cost of electrical installation and the cost of some of the DC components is already included in the budget of the project. This fact could make DC a more attractive alternative option for new buildings because it does not increase the capital expenses. In fact, the cost of a DC-based system with PV and battery storage is lower compared to an AC-based system (see Part B).

In addition, in the case of new districts/neighborhoods, DC has already caught the attention of actors in the energy sector, as an alternative solution for distributing electricity. According to Samuel de Guchteneire (consultant at Alliander), the market potential of DC is difficult to be assessed at the moment. However, the development of DC distribution networks is more likely to start from green fields; new neighborhoods that have no access to electricity. Having the option to opt for a DC connection offered by the grid operator will most likely facilitate adoption by the customers’ side. Currently, Alliander develops a DC distribution grid in Lelystad that will mainly connect commercial buildings. Additionally, it plans to implement DC grids for the connection of residential buildings in 4 new districts within 2017. Each of these projects will connect 6-20 households.
Find believers: The DC micro grid that is being designed in the framework of the DC-Flexhouse project is a technological solution that contributes to sustainability and offers energy autonomy for the end-user. Therefore, involved companies should target environmentally conscious consumers, such as private household owners with a "green heart" and neighborhood cooperatives with a mission to develop sustainable neighborhoods. Studies on the adoption of sustainable behavior have shown that citizen participation in the development of new products, services and systems, such as eco-towns, can increase legitimization, market acceptance and sustainability impact. Cooperative networks can be a powerful actor for promoting participation in sustainable urban development [68].

Be patient and let the market develop through pilot and demonstration projects: Especially in the case of smart grid applications, DC technology will most probably become operational through protected test beds with the support of public financing, as is the case with the development of smart grid concepts in the AC-world. The Dutch paradigm for the smart grid development shows that approximately 10 years of experimentation with R&D and pilot and demonstration projects were needed before moving to large-scale implementation projects (see Figure 8). Active involvement of actors from the energy sector and support from municipalities are thus essential for capturing a market share in the smart grids market.

The table below aggregates potential early adopters for DC technology in the built environment:

Table 7. Potential early adopters of DC technology in the built environment

<table>
<thead>
<tr>
<th>Technology</th>
<th>Early adopters</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC distribution for power supply of electronics (USB-C wall sockets)</td>
<td>• Private household owners with high income/brand-sensitive (Apple)</td>
</tr>
<tr>
<td>DC distribution for power supply of electronics and LED lighting</td>
<td>• Private household owners with high income/brand-sensitive (Apple)</td>
</tr>
<tr>
<td></td>
<td>• Commercial buildings/ offices with innovative image</td>
</tr>
<tr>
<td></td>
<td>• Educational buildings (schools/universities)</td>
</tr>
<tr>
<td></td>
<td>• Data centers/ICT</td>
</tr>
<tr>
<td>DC distribution and integration of PVs and storage/smart DC grid</td>
<td>• Agricultural buildings</td>
</tr>
<tr>
<td></td>
<td>• Neighborhood cooperatives with a vision for sustainability</td>
</tr>
<tr>
<td></td>
<td>• Large scale buildings renovation initiatives (e.g. Stroomversnelling)</td>
</tr>
<tr>
<td></td>
<td>• Private households with high income/“green heart”</td>
</tr>
<tr>
<td></td>
<td>• Newly built buildings</td>
</tr>
<tr>
<td></td>
<td>• New neighborhoods/districts</td>
</tr>
</tbody>
</table>
7.2.3 Market outlook

Figure 19 shows market scalability as a function of time. As explained in the previous Chapter, if DC technology achieves a mass roll-out influencing the current energy regime, it will do so through the adoption by early markets. It can be expected that DC will gain a share in the commercial/educational buildings market before it does in the residential sector. However, this target group of early adopters also includes residential segments through existing large scale renovation initiatives (e.g. the Stroomversnelling) and cooperatives with a mission to promote the development of sustainable neighborhoods.

Based on the technology adoption lifecycle proposed by Rogers [69], this early market covers 2.5% to 15% of the whole market. However, penetration in this early market will facilitate penetration in the mainstream market a later stage. As soon as DC starts gaining a market share, more and more potential customers will become aware of the technology.

The existence of a DC distribution grid where buildings can be connected will accelerate this process. Alliander (the largest energy grid operator in the Netherlands with 2.8 million customers) is already exploring the benefits of DC distribution grids as a way to facilitate the energy transition, and has expressed its interest in the outcomes of the DC-Flexhouse project (interview with Samuel de Guchteneire, consultant at Alliander and responsible for DC projects). In the case the DC micro grid designed within the DC-Flexhouse project on building level proves to contribute to energy savings,
reduction in CO2 emissions and reliability in congestion management on the distribution grid, it will most likely be supported by Alliander.

A next interesting segment in the mainstream market is all electric buildings that will be designed to be energy neutral and come with Energy Performance Contracting (EPC) (see adopter groups under pragmatists in Figure 19). The high acquisition costs of the DC components and social resistance to change will likely be prohibitive factors for adoption by the mass residential market (private households) in the early stages. However, as soon as the cost goes down (economies of scale), the availability of DC-ready appliances increases and an increasing number of people become aware of the DC technology, DC can gain a share in the mainstream market as well.

7.3 The DC innovation ecosystem
The transition to DC cannot be pursued by one single actor. According to the Transition Management approach, such an innovation will be facilitated through the creation of social networks or innovation ecosystems. An innovation ecosystem is a network of organizations and companies that share a common vision and combine their services and products together to deliver a value proposition for the end customer. In turn, the actors within this ecosystem need to capture value from supporting this innovation. Ron Adner in his book “The Wide Lens: A New Strategy for Innovation” stresses that the likelihood of success of an innovation depends on the involvement of 2 types of actors: the co-innovators and the adopters within the value chain. In the DC case, co-innovators are the actors that also need to innovate for the DC innovation to matter, while adopters within the value chain are actors that need to embrace the innovation before the end customer can assess the full value proposition.

7.3.1 Actors within the DC innovation ecosystem
The analysis of the ecosystem is the first step to identify the necessary actors, their roles and how they interact with each other. Figure 20 depicts the DC innovation ecosystem. Within this ecosystem, a number of different groups and actors can be distinguished according to their functions, responsibilities and needs.

Firstly, the commercialization of DC highly depends on the availability of DC components (power supply equipment, DC/DC converters, electronic fuses, DC-ready devices, etc.). Therefore, actors that should co-innovate are:

- Manufacturers of electronics (adoption of USB-C standard)
- Manufacturers of household appliances
- Manufacturers of power supply and safety equipment
- Manufacturers of battery and photovoltaic systems

Respectively, potential actors that should adopt DC technology before reaching the end customers (“channels”) are:

- Construction companies
- Electrical installation companies
- Advisors and Consultants active in the built environment
- Energy Service Companies (ESCos) (usually perform Energy Performance Contracting (EPC))

These actors (“channels”) influence the potential end customers as presented in Chapter 7.2 in their decision making. They should be aware of the developments in LVDC power.

The “facilitators” are the indirect actors that can support the transition to DC. They consist of the government, regulators and municipalities. Considering other sustainable innovations such as solar technology, it can be seen that the role of the government was essential for mass roll-out [35].
This Chapter provides a more extensive description of the actors that also have to innovate in order for the DC innovation to reach the market.

**Energy sector**

Grid operators: The term “grid operator” refers to the undertakings of operating, building, maintaining and planning of the electric power transmission and distribution networks.

- **Transmission System Operator (TSO):** TenneT is the single national TSO in the Netherlands. TenneT’s main tasks are to maintain and manage the transmission networks, monitor electricity supply, resolve large-scale disruptions in electricity transmission and maintain the balance between supply and demand. Moreover, TenneT is responsible for the connection of all grid users at the transmission level and the connection of Distribution System Operators (DSO). TenneT is also required to develop the electricity market and promote the establishment of an integrated Central Western European market. TenneT provides connection, transmission and system services. Tariffs and conditions for these services are regulated by the Authority of Consumers and Markets (ACM) [70].

- **Distribution System Operator (DSO):** The electricity distribution network is operated by eight distribution companies, through concession agreements. Enexis, Liander, Delta and Stedin manage more than 90% of the distribution network in terms of connections. The DSOs provide the connections of electricity consumers at the distribution level and charge a service fee accordingly.
Energy producers: The Dutch power generation market is moderately concentrated, with four major players: Nuon/Vattenfall, Essent/RWE, E.ON and Electrabel/GDF SUEZ. Together, they managed 55% of installed power capacity in 2013 [71].

Energy suppliers: An energy supplier is the utility company that supplies electricity to end consumers through contractual agreements. Moreover, energy suppliers are the actors that will provide new services, real-time information, energy efficiency services and dynamic energy pricing concepts with Time-of-Use (ToU). The suppliers also provide local aggregation of demand and supply in order to increase the effectiveness and efficiency of the electricity supply at all voltage levels. Energy suppliers are not always energy producers. The Netherlands has over 40 energy suppliers that each offer different contracts and conditions [72].

Programme responsible parties: TenneT uses a system of balance responsibility to keep the supply and demand of electricity in check. Connected parties are responsible for informing grid administrators of their planned electricity production, consumption and transport needs. If their actual consumption and production differs from what they forecast, imbalances occur, which can ultimately affect the reliability of the grid. Programme responsible parties (PRPs) have the responsibility to maintain the balance in supply and demand during a given time period. This time period called a program time unit (PTU) is 15 minutes. Authorized PRPs inform TenneT daily about their planned transactions for the next day, and the networks they will use for transporting the electricity. The sum of the transactions for each PRP is called an energy programme (e-programme). During operation, PRP’s are required to follow the planning. The regional DSOs inform the TSO about how much electricity each PRP actually consumes and produces. The difference between the amounts in the e-programme and the actual measured values is the imbalance. PRPs can be the producers and suppliers themselves, or an authorized entity.

Aggregators: The aggregator is a new role that emerged as a result of the renewable transition in the energy sector. This entity could be responsible for local aggregation of supply, like small-scale decentralized PV systems and demand response capabilities [73]. In cases where the aggregator is not a supplier, it maintains a contract with the supplier.

Providers of Technology, Products and Services – Co-innovators

In the DC case, key technology providers are manufacturers of appliances and electronics, conversion products and power supply equipment. Within the overall transition towards smart grids, new market opportunities arise for these manufacturers. Big companies such as ABB, IBM, and Siemens have shifted their interest towards smart technologies for the electricity grid, while also many start-ups have emerged over the last years. These companies participate in R&D and pilot projects in collaboration with research organizations and/or actors from the energy sector in order to experiment with different concepts and develop their portfolio of products and services for the future.

 Adopters within the value chain - Channels

This group involves companies active in the construction sector, such as construction companies, electrical installers and consultants. The construction sector was heavily affected by the economic crisis that started in 2008. New residential construction in Europe, which was the main pillar of construction activity until 2006, followed a clear downward trend since 2007, -3.8% in 2007 and -14% in 2009. Since mid-2008, this trend has mainly due to the deterioration in private investor’s access to credit, as well as householder’s lack of confidence in future market prospects [74]. Rehabilitation and maintenance were not heavily affected by the crisis mainly due to the support in investments by public entities. In general, both residential and non-residential markets benefit from the European and
national measures targeting the renovation and retrofitting of buildings as a means to reduce the environmental impact of buildings and accelerate economic recovery through support to a high labor-intensive service. During the first quarter of 2016, construction output in the Netherlands was 17% higher than it was at the lowest point. However, the country has not yet returned to pre-crisis levels. By early 2016, Europe’s building production was still 21% below pre-crisis levels.

In order to overcome the crisis, companies active in the sector are trying to find new market opportunities and boost their competitiveness. According to Wil Paulus (owner of EPM electrical installation company and member of DC-Flexhouse project), at this time it is essential to innovate in order to survive and compete in the market. The transition in the energy sector and the changing preferences of energy consumers act favorably in this respect. Companies explore ways to penetrate the building services and smart grids sectors, offering solutions such as energy efficiency measures and Building Management Systems (BMS) to minimize operational costs and Demand Side Management to enable flexibility in electricity consumption.

**Facilitators**

**Government and policy makers:** These entities are in charge of defining legislation and metrics for areas such as environmental policy, social policy, energy policy and economic policy. They are also responsible for the authorization needed to develop the electricity grid infrastructure. The role of the government and policy makers has been proven to be essential when it comes to sustainability transition and the breakthrough of radical innovations. Technologies that contribute to sustainability such as photovoltaics and wind turbines have been supported both through formal structures (like public financing schemes) and informal ones (like environmental campaigns to increase environmental awareness and eventually change cultural values).

**Municipalities:** The group of municipalities constitutes a facilitator in terms of financial support and dissemination. Municipalities in the European Union are defined as the second level administrative divisions and the main decision maker in implementing energy-efficiency measures. Most of them have already set their goals for future-proof, energy-neutral or smart city solutions. In this respect, it can be assumed that municipalities could act as the key agent for market development. In the Netherlands, there are 393 municipalities and 3 public bodies.

**Standardization bodies:** Standardization bodies are responsible for the standardization of all relevant elements and components within the electricity supply chain which in turn leads to harmonization of
relevant services, support towards removing barriers to trade, creating new market opportunities and reducing manufacturing costs [75].

Academia: The research community has a critical role to play: without research there is no innovation and without innovation there is no evolution. Additionally, there is a need to educate and prepare adequate workforce to tackle future challenges.

7.3.3 Value creation within the DC context
In order for the DC innovation to be a commercial success it has to create value for all actors involved in the DC innovation ecosystem and the target markets. Key actors are different for different system designs and different markets, while the value proposition could also differ among market segments.

Additionally, the success of DC is also influenced by exogenous factors (e.g. change in net-metering policy, support by the government, etc.). In general, industry representatives (including DC-Flexhouse project members) are not in favor of, or even disapprove, subsidies because they argue that a technology should be able to survive in the market without support from the government. In the transition management literature, however, subsidies and other niche protection/shielding tools are often deemed as necessary to give the new technology (DC in this case) a chance to develop and prove itself [35] [76].

The following Chapters present future scenarios for the commercialization of DC. Rather than being exhaustive, the future scenarios provide options for value creation for various market segments as well as barrier considerations.

To analyze the impact of DC technology in terms of how actors within the DC innovation ecosystem can create value and earn money in the process, this study adopts the business model framework proposed in [77]. This framework distinguishes three components: actors, ecosystem’s value proposition (EVP) and customer segments.

1. Actors. The actors are the companies and organizations who create customer-oriented value together. The actors within the DC innovation ecosystem have been presented above.

2. Ecosystem’s value proposition (EVP). The EVP is the integrated output of the whole ecosystem, as targeted to the end customers. It is important to understand the EVP as it is actually perceived by the end customer and not as the actors might perceive it. According to [29], there is a fundamental problem for companies that want consumers to embrace innovations. While developers and researchers are already convinced for the value of their products, consumers are usually unable to see the need for it. This conflict results in a mismatch between what innovators believe consumers want and what consumers truly desire.

3. Customer segments. Classical marketing theory claims that a value proposition is more effective on the market when targeted to sub-Chapters of the market referred to as customer segments [77]. This component of the business model framework therefore specifies who the target audiences are.
Furthermore, to understand how each of the actors actually accomplishes his/her module and why they might want (or not want) to be part of the ecosystem, the business model framework analyzes additional elements under each actor: value addition, resources, activities and value capture [77].

1. Value addition. From the viewpoint of the whole ecosystem, each of the actors has a particular contribution to the EVP, which is referred to as value addition of the organization.

2. Resources. This element describes the most important assets that form the basis for the value creation for that particular actor.

3. Activities. This element addresses what is actually done to accomplish the value addition and earn sufficient returns in the process.

4. Value capture. Actors are naturally interested in gaining benefits, which can be both financial and non-financial. For example, for a government, welfare of their citizens is a benefit that might justify the lack of financial gain. Similarly, for a grid operator, achieving its target for CO2 emissions is considered as a benefit. For-profit companies typically assume financial incentives.
Scenario 1:

Table 8. DC micro grids in commercial/educational buildings and key elements forming the future market potential

<table>
<thead>
<tr>
<th>Technology design</th>
<th>DC micro grids on building level that come with an energy management system for load management (the goal is to match renewable generation with building demand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential system components</td>
<td>Photovoltaics, heat pump, LED lighting, electronics (potentially other appliances that could be shifted to match renewable generation, as presented in Chapter 7.1.1)⁹</td>
</tr>
<tr>
<td>Market segment</td>
<td>Commercial/educational buildings (in general buildings with high demand for lighting and computing)</td>
</tr>
<tr>
<td>Actors</td>
<td>* manufacturers of system components, power supply equipment and converters * construction industry * energy service companies (ESCos) * grid operators * government</td>
</tr>
<tr>
<td>Value creation</td>
<td>* for grid operators: less investment in grid reinforcement, less energy losses and CO2 emissions, lower operating cost * for building owners and/or users: lower contracted power, energy autonomy, lower operating cost, load management and robustness to failure (see Chapter 6.1.2), increased TVO, comfort</td>
</tr>
<tr>
<td>Technology development</td>
<td>* Proved savings in operating costs * Savings in capital costs (or at least similar to the AC case) * Secure end-users’ comfort * Reliable operation</td>
</tr>
<tr>
<td>Barriers and preconditions</td>
<td>* Uncertainty about electricity prices * Change in net-metering policy will make consumption of own generation a more attractive solution * Regulations for peak-load pricing * Update of building codes for DC * Standardization of LVDC power (distribution, equipment) * Wide adoption of USB-C standard by electronics manufacturers * Perceived financial incentives by financers * Unawareness about DC technology * Unfamiliarity with the possibilities offered by DC for both the market and the industry * Low anticipated rate of profitability of a new business/product in the early phases deters managers from engaging in its development * Policy support</td>
</tr>
</tbody>
</table>

⁹ In the case of commercial buildings, battery storage might not be necessary, because building occupancy matches with PV generation. For real projects, a study should be done for each individual customer taking into account consumption profile, generation capacity and the desire of the building owner for consumption of own generation. The system design should meet customers’ needs.
**Discussion**

The in-building DC installation is a smart grid that connects photovoltaics and DC loads without AC/DC converters. The DC output from PVs is directly consumed by DC loads (heat pumps, LED lights and electronics). That means that the building consumes the energy that is generated by its own PV installation for present DC loads.

Therefore, the building owners can choose a limited power supply, which leads to a reduction in the connection fees they pay to the grid operator. Operating costs for electricity consumption from the grid decrease. The electricity savings due to the elimination of AC to DC conversion steps depend on the DC load. Higher DC load translates to higher electricity savings and more optimized use of renewable energy. In addition, the DC installation creates a green and innovative image, a fact that increases the TVO. Some companies determine whether an investment is worthwhile based on other aspects in addition to the TCO, such as reduction of carbon footprint, innovative image and working capital efficiency.

Furthermore, the installation of USB-C wall sockets allows the elimination of power adapters for electronics. Laptops can be directly plugged in the sockets using only the USB cable. This provides comfort and an aesthetically pleasant environment for the end-users (employees). Research shows that workplace innovation seems to have a positive relationship with employee performance and commitment [78].

The market potential within the commercial sector depends on factors that are out of the control of the companies that are interested in promoting DC. The economic viability of the in-building DC installation is influenced by future electricity prices and change in regulations regarding the support of photovoltaic technology. The net-metering policy that was the major success driver for solar technology, and energy management solutions for the exploitation of own generation conflict each other.

The actors that have to co-innovate in order to realize this scenario are: manufacturers of solar panels and converters, luminaires, heat pumps and electronics. The likelihood of co-innovation by electronics manufacturers is high as a result of the development of the USB-C standard. The rest of the actors have to be convinced for the market potential and make the upfront investment. Wider adoption by co-innovators will increase the possibility of wider adoption by the market. People will feel safer if they know they have easy access to DC components in case of failure.

Finally, the involvement of grid operators could be essential for market success. The existence of a DC distribution grid reduces the capital investment for the financer by the cost of the bidirectional inverter. The benefit for the grid operator is reduction in capital for grid expansion and operating costs (less transport losses). Of course, this value for the grid operator will be realized via the connection of a big number of buildings within a district (Figure 24).
Manufacturers of DC system components comprise both manufacturers of power supply equipment (such as ABB) and manufacturers of appliances/devices such as proper luminaires and heat pumps that can work directly with DC (not part of DC-Flexhouse project). Actors from the PV sector are manufacturers of solar panels and manufacturers of converters. These components have to be designed as specified by the company Direct Current BV (initiator of DC concept) in order to be integrated in the DC installation. Actors within the construction sector have to be aware of the technology because they usually are the parties that influence building owners for the initiation of renovation projects. The likelihood of market success of this scenario highly depends on adoption by innovators in the market.
Figure 24. DC ecosystem business model for commercial buildings in the case of involvement of grid operators. The likelihood of success of this scenario is higher compared to the scenario where the energy sector is not involved. The existence of a DC distribution grid lowers the needed capital investment from the customer’s side. In this scenario, customers can also be rewarded by the grid operator for reducing peak load.
Scenario 2

Table 9. DC micro grids in residential buildings and key elements forming the future market potential

<table>
<thead>
<tr>
<th>Technology design</th>
<th>DC micro grids on building level that come with an energy management system for load management (the goal is to match renewable generation with building demand)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential system components</td>
<td>Photovoltaics, battery storage, heat pump, LED lighting, electronics, white goods and other appliances that enable flexibility in energy consumption, as presented in Chapter 7.1.1.</td>
</tr>
<tr>
<td>Market segment</td>
<td>Residential buildings (mainly housing corporations)</td>
</tr>
</tbody>
</table>
| Actors | * manufacturers of system components, power supply equipment and converters  
* construction industry  
* energy service companies (ESCos)  
* grid operators  
* government |
| Value creation | * for grid operators: less investment in grid reinforcement, less energy losses and CO2 emissions, lower operating cost  
* for building owners and/or users: lower contracted power, energy autonomy, lower operating cost, load management and robustness to failure (see Chapter 6.1.2), increased TVO, comfort |
| Technology development | * Proved savings in operating costs  
* Savings in capital costs (or at least similar to the AC case)  
* Secure end-users’ comfort  
* Reliable operation |
| Barriers and preconditions | * Uncertainty about electricity prices  
* Change in net-metering policy will make consumption of own generation a more attractive solution  
* Regulations for peak-load pricing  
* Update of building codes for DC  
* Standardization of LVDC power (distribution, equipment)  
* Wide adoption of USB-C standard by electronics manufacturers  
* Perceived financial incentives by financers  
* Unawareness about DC technology  
* Unfamiliarity with the possibilities offered by DC for both the market and the industry  
* Policy support |

Discussion:

The in-building DC installation in scenario 2 is similar to the scenario described in the previous paragraphs. However, in this case the system should include storage. For residential buildings there is a mismatch between the PV output and building occupancy. In the absence of storage, only loads coincident with PV system output can direct DC supply. Therefore, the value of DC in terms of electricity savings depends on the integration of storage.

Additionally, for residential buildings except for electronics and lighting other DC-ready appliances have also to be available. Otherwise, stored energy (in DC form) has to be again converted to AC in
order to supply AC loads. This implies a loss in energy efficiency and contradicts the value proposition for energy savings.

Since the full potential of DC for building owners lies in the integration of more components to the system, the ecosystem of co-innovators presented in scenario 1 should expand to also include manufacturers of battery storage and other white goods.

Similarly to the commercial sector, the building/household consumes the energy that is produced by the PVs. The building owners can choose a limited power supply, which leads to a reduction in the connection fees they pay to the grid operator. Operating costs for electricity consumption from the grid decrease and renewable energy is better exploited due to the elimination of AC to DC conversion steps.

Although the technology might be adopted by innovators and frontrunners, in order to reach a bigger market it should indeed provide savings in operating costs and impose lower or at least similar capital costs. Although some housing corporations consider the TVO, payback period is highly considered to assess whether an investment is worthwhile. According to Marco Timmermans (Engineer at HOMIJ DEC, involved in a project for DC installation in 14 apartments in Strijp-S neighborhood in Eindhoven), the company (Bouwinvest B.V.) that decided to invest in the renovation of the apartments with DC technology will further adopt DC only in the case it offers financial benefits, either lower operating costs or lower capital costs. Especially for social housing corporations TCO is considered as highly important because they have to finance themselves.

In contrast to commercial buildings, another market barrier in the rental housing market is the potential misalignment with what the tenant wants. Apartments with DC power supply imply that tenants are willing to invest in DC appliances. In the case of commercial buildings, computing equipment is provided by the employer, who can also be the decision maker for choosing to invest in such a system.

The market potential again depends on factors that are out of the control of the companies that are interested in promoting DC. Market adoption is affected by the change in net-metering policy, but also technological development in the AC world (e.g. improvement of efficiencies of AC to DC power converters). The withdrawal of the net metering policy will make storage a more economically attractive technology for future PV system owners.

The likelihood of market success will be increased by the involvement of grid operators. The existence of a DC distribution grid reduces the capital investment for the financer by the cost of the bidirectional inverter. The benefit for the grid operator is reduction in capital for expansion of the AC grid and in operating costs (less transport losses). Apparently, this value for the grid operator will be realized via the connection of a big number of buildings within a district.
The value proposition for this segment is the same as it is for commercial buildings. However, electricity consumption in private households is rather low. Therefore, for the same improved energy efficiency offered by DC, the payback period of the investment in residential buildings is longer compared to commercial buildings. In addition to the system components in a DC installation in commercial buildings, the system for residential buildings should include battery storage and more DC appliances, which increases the necessary capital for the financier. The chances for commercial success highly depend on the adoption by housing corporations with an innovative perspective.
Figure 26. DC ecosystem business model with the involvement of grid operators. The existence of a DC distribution grid increases the likelihood that DC innovation will be embraced by the market. Buildings connected to the same grid can exchange renewable energy using the DC distribution grid.
**Scenario 3:**

**Table 10. DC smart grids and key elements forming the future market potential**

<table>
<thead>
<tr>
<th>Technology design</th>
<th>DC smart micro grids on building level that provide flexibility in energy consumption and/or production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential system components</td>
<td>Photovoltaics, battery, heat pump, water boiler, LED lighting, electronics, white goods and other appliances that enable flexibility in energy consumption, as presented in Chapter 7.1.</td>
</tr>
<tr>
<td>Market segment</td>
<td>residential and commercial buildings</td>
</tr>
</tbody>
</table>
| Actors | * manufacturers of system components, power supply equipment and converters  
* construction industry  
* energy service companies (ESCos)  
* energy sector  
* government |
| Value creation | * for grid operators: less investment in grid reinforcement, less energy losses and CO2 emissions, lower operating costs, congestion management and robustness to failure (see Chapter 6.1.2)  
* for players in the electricity market (energy suppliers, energy producers, prosumers, aggregators, PRPs): reduced imbalance, less price volatility (the same value is offered through the deployment of DR in the AC-world)  
* for building owners and/or users: additional revenues for providing flexibility services, lower contracted power, energy autonomy, electricity savings, less capital costs (in case of connection to DC distribution grid), comfort |
| Technology development | * Proved savings in operating costs  
* Savings in capital costs (or at least similar to the AC case)  
* Secure end-users’ comfort  
* Reliable operation |
| Barriers and preconditions | * Uncertainty about electricity prices  
* Economic viability of battery storage (change in net-metering policy will make battery storage a more economically attractive solution)  
* Involvement of actors from the energy sector/provision of the option for connection to a DC distribution grid  
* Update of building codes for DC  
* Standardization of LVDC power (distribution, equipment)  
* Regulatory for deployment of smart grid applications, remove regulatory barriers and clearly define the roles and responsibilities of all (future) power system stakeholders within the smart grid  
* Perceived financial incentives by end-users  
* Unawareness about DC technology  
* Unfamiliarity with the possibilities offered by DC for both the market and the industry  
* Policy support |
Discussion:

In this scenario, buildings are positioned in the smart grids market. DC could be interesting for both residential and commercial segments. In the case of residential buildings, housing corporations that own and manage a big number of buildings seems to be a better fit compared to individual private households. In order to capture the potential value creation for this scenario, it is first essential to understand the structure of the electricity markets and the benefits of flexibility in energy consumption for the power system in the AC-world.

The electricity market

Energy producers and suppliers, which are not necessarily PRPs (see Chapter 7.3.2) trade electricity on the wholesale electricity market. The wholesale electricity market distinguishes long-term forward and short-term spot markets for trading of electrical energy [79].

- **Forward markets**
  Long-term trade occurs in forward markets and can either be done using over-the-counter bilateral contracts or through futures exchanges, which trade standardized future contracts [79]. Usually these long-term contracts are signed one to several years in advance.

- **Spot markets**
  As a result of the electricity market liberalization, various competitive sport markets were established across the EU. The Amsterdam Power Exchange (APX) was the first spot market in Europe\(^\text{10}\). Typically, a spot market consists of a day-ahead and an intra-day market. In both markets suppliers can make bids for selling and buying energy and the market operator determines equilibrium market clearing price and volume.

- **Ancillary service markets**
  To keep the system in balance, TenneT set-up a so called balancing market [79]. This is a single-buyer market for control and reserve power. Within the balancing market (also referred to as imbalance market), suppliers can make bids day-ahead. Once these bids are placed the TSO has the right, but not the obligation to activate them. Depending on the demand for balancing power and the bid price order bids are activated. If a bid is activated, the supplier is informed by the TSO [32]. An example of the Dutch imbalance market can be seen in Figure 29.

Often, base load is contracted bilaterally or on the future markets, while the variable consumption is purchased on the spot markets.

The value of flexibility in energy consumption

The implementation of smart grids in terms of flexibility in energy consumption and/or production is expressed by both the grid and the energy market value.

\(^\text{10}\) Over the years APX merged with various other European exchange markets. Today it is part of the APX Group, which operates the sport markets for the Netherlands, United Kingdom and Belgium. [https://www.apxgroup.com/](https://www.apxgroup.com/)
Value creation for grid operators: On the distribution level, flexibility can contribute to congestion management and the reduction of peak loads, mitigating the need for costly grid expansion. This is a benefit for grid operators, which in turn can be translated to benefits for the energy consumers (e.g. rewards for avoidance of peak loads). The rising integration of renewable energy sources (RES) and the expected increase in electricity demand will have a material impact in the grid. Grid operators will have to invest in grid reinforcement in order to meet the demand for transport capacity. Additionally, the energy transition drives the need for smart grids. In order to implement congestion management the grid operator will have to upgrade the grid with the integration of ICT equipment. Safe operation of the grid relies on the communication among these devices. Therefore, smart grid applications can be implemented with the existing AC infrastructure, however, the DC grid offers increased robustness to failure as explained in Chapter 6.1.2. Even if communication fails, safe operation of the grid is secured.

Value creation for end-users: For the energy consumer, contributing to congestion management and the reduction of peak demand translates to a reduction in operating costs. Contracted power can be reduced (lower connection fees) and additional charges for creating peaks can be avoided. At the moment only large consumers pay a tariff to the grid operator for the peak they create. However, the goal of the energy sector in the future is to apply charges also for residential consumers in order to minimize peaks and avoid investments in increasing the grid capacity. In DC grids it will be easier to implement dynamic pricing and peak-load pricing also for residential consumers. It is easier to create new regulations for new energy systems than change the existing ones (input from Samuel de Guchteneire, Alliander).

Value creation for actors in the energy market: As explained in Chapter 7.3.2, PRPs are responsible for informing the TSO about the consumption and generation planning for the next day (e-programme) and the networks they will use for transporting the electricity. During operation, PRPs are required to follow the planning. The difference between the amounts in the e-programme and the actual measured values is the imbalance. Costs for correcting actions are retrieved by penalties for the parties that cause the imbalances. It is expected that electricity markets will become more volatile as the share of intermittent DG increases and the electrification continues. The imbalance markets will become more important as volatility increases. Responding to imbalance (by adjusting consumption or generation) can be profitable while causing imbalance can be costly.

Value creation for end-users: The benefits of flexibility in energy consumption translates to benefits for the end-users as well. One option is that energy can be purchased at optimal moments. The market volatility is used to gain a financial advantage. From a comparison of on- and off-peak prices on the spot markets (Figure 28) [80], it can be concluded that an advantage of 0,04 €/kWh can be reached.
Secondly, when flexibility is used to balance a portfolio, the portfolio imbalance and deviation from the e-programme can be reduced. Flexibility can be offered to a PRP through contracting. A temporary reduction of demand can be seen as negative production and is as such equally valuable as additional generation capacity. In this respect, the value of providing reserve power on the imbalance market is approximately 0.02 €/kW (Figure 29). This number is based on imbalance clearance data from TenneT (for 13/12/16) [81].

Figure 28. Example of spot market settlement on the Dutch APX market (accessed on 15/12/16) [80]

Figure 29. Example of the Dutch imbalance market prices (accessed on 15/12/16) [81]

In the smart DC grid that is being designed within DC-Flexhouse, congestion management and supply and demand balancing are focused on building level and are based on available supply and demand (by checking the voltage level on the DC bus) and not on financial incentives. However, as is the case with the implementation of smart grids in the AC-world, financial incentives are essential to define potential business models and attract customers. Otherwise, DC innovation faces the danger of remaining stuck in small markets (tech savvies, people with passion for sustainability and/or desire for energy autonomy). Taking the example of the current situation, similar principles can be applied in future DC grids.

To sum up, in addition to electricity savings and consequent savings in operating costs, this scenario considers that building owners and/or users (financers) have an additional revenue stream for
providing flexibility services and/or reducing contracted power. Because energy savings from switching to DC per se might not a strong convincing factor to attract investments and reach the mainstream market, this scenario creates more value for potential customers.

The identification of the economic value of flexibility in the DC-world is out of the scope of this project. Actually, the economic value of flexibility is difficult to be assessed at these early stages. It requires a thorough cost-benefit analysis on district level and not only on building level, in combination with the use of experimental data that will be available after the end of the DC-Flexhouse project. However, the estimation of the economic value of flexibility in the AC-world provides guidelines for potential value creation in the DC case.

This scenario requires the involvement of actors in the energy sector. Grid operators have already shown interest in the DC case. Alliander will implement a new DC grid mainly for the connection of commercial buildings within 2017 (Lelystad), while it also plans to implement pilot projects for the connection of residential buildings. The focus at the moment is on new neighborhoods/districts. These pilot projects will validate whether DC distribution grids in parallel with AC grids is a better option than only AC grids. According to Samuel de Guchteneire (consultant at Alliander), the key factors for supporting the implementation of DC grids (and the DC technological solution that will be the outcome of DC-Flexhouse project) are threefold:

- customer-driven: legally obliged to provide connection to the grid for every customer, responsible for satisfying customer needs (than means that in case customers show interest, DC will most likely adopted by grid operators)
- grid-driven: solutions that minimize both capital and operating expenses of the grid
- environment-driven: even if more expensive, solutions that contribute to a reduction in CO2 emissions are preferred
Figure 30. DC business model for DC smart grids. The market includes both commercial and residential buildings. This scenario represents projects on district level. In order to be realized, the involvement of grid operators and the alignment of the desires of the building owners within the district are required. Additional financial incentives can be provided to potential customers such as rewards for reducing peaks (peak load pricing, dynamic pricing) (benefit for the grid operator) and matching renewable generation and demand (benefit for PRP and as a consequence for energy suppliers).
8. Action plan and recommendations

This Chapter presents an action plan for companies and organizations involved in the DC-Flexhouse project. Based on my personal observations as well as guidelines inferred from the innovation and transition management literature, a set of recommendations towards the commercialization of DC is developed. At the moment, it is too difficult to accurately assess the market potential and answer the question whether DC is a good business case for both the industry and the market. However, if parties interested in promoting DC technology follow the recommendations articulated in the action plan (Figure 33), the likelihood of commercial success increases. In this respect, to build internal momentum and increase the chances of commercial success, the actors within the DC innovation ecosystem should:

1. **Experimentation and learning-by-doing:** Rather than trying to develop a prescriptive deliberate strategy for the transition to DC, the literature on transition theories suggests that for radical innovations, a business strategy should be a continuous process of learning-by-doing. Initial market application is input for subsequent market application in order to get feedback from the customers and other relevant actors, improve the technology and learn about market characteristics. Markets should not be so much picked on the basis of expected profits, but rather on the basis or learning [16].

   For example, the DC installation proposed within the DC-Flexhouse project could be more attractive for new constructions compared to renovations. Based on initial estimations (see Part B), the capital cost of a DC installation with PV and battery storage, and connection to a conventional AC distribution grid, is 6% lower compared to a same system that is based on AC power. Remarkably, the capital cost of a DC-based installation is almost half the capital cost of the AC-based installation for new residential buildings in the case of connection to a DC distribution grid, while DC is already being explored by actors in the energy sector (Alliander) as an alternative way for distributing electricity in new neighborhoods. Therefore, although existing buildings constitute a substantially bigger market compared to new buildings, DC might in the beginning be a more attractive solution for new constructions.

   The transition management literature suggests that sustainable innovation journeys start from early niche markets and technological niches[11] [82]. Potential early adopters have been indicated in Chapter 1.1.1. Adoption by groups of early adopters and/or implementation of more pilot projects will help DC to develop and prove itself (Figure 31).

---

[11] Technological niches are protected spaces that allow nurturing and experimentation with the co-evolution of technology, user practices and regulatory structures [82]. In this respect, it can be said that DC-Flexhouse and other subsidized projects for the development of DC micro grids and respective DC components constitute technological niches.
2. **Learn and improve or change**: People often cannot express their opinion and needs for technologies that are not yet existing or fully developed [16]. In the DC case, people cannot understand what the differences between AC and DC are, and how having a DC grid next to the conventional AC grid would affect their behavior. In the case of innovations that do not satisfy an identified market need, developing prototypes and implementing pilot projects with the participation of end-users is beneficial in two ways: 1) the involved actors in DC technology development will learn from feedback from various end-users and use this feedback to optimize the design of the system, and 2) end-users will become aware of the technology and its benefits.

Especially for the future scenario of DC smart grids (see scenario 3 in Chapter 7.3.3) where buildings provide congestion management services to the grid, end-users must not experience any loss of comfort. Most probably, DC smart grids will become operational through pilot projects with the active participation of end-users (this is also the case with the deployment of smart grid applications in the AC-world, e.g. PowerMatching City, Your energy moment, etc.).

3. **Develop social networks**: TM emphasizes the role of social networks in pursuing market success for radical innovations [22]. Social networks have to ensure that support is broad (i.e. involving plural perspectives) as well as deep (i.e. implying substantial resource commitments) [82]. Societal actors such as governments, business, scientists and non-governmental organizations create formal or informal networks because of partially joint interests and the willingness to temporarily share certain resources in order to work for shared objectives [22].

During my involvement in the DC-Flexhouse project, I found out that there are also several other initiatives for the development of DC micro grids in the Netherlands, but they apparently do not have a shared network. Aligning lessons and experience from different projects will broaden the social network and increase the chances of DC penetration into the current energy system. A central platform will also facilitate better coordination of DC initiatives. Therefore, a shared platform or forum needs to be created for sharing experiences, needs and results of various projects.

4. **Develop positive expectations**: In the case of such radical innovations, it is important to develop positive expectations among societal stakeholders that are:
a) robust (that is, shared by more actors)
b) more specific (if expectations are too general they do not give guidance), and
c) credible (substantiated by multiple projects) [82] [35].

Expectations development should address both the actors within the DC innovation ecosystem and the market. The prototype developed within the framework of DC-Flexhouse has to act as a demonstrator for positive expectations development. Positive expectations build up momentum and increase the likelihood of adoption by the market, both building owners and grid operators. The findings of DC-Flexhouse project should be used to also capture political attention. The role of policy support in the success of other sustainable innovations has been proven crucial [82] [35].

5. **Ensure participation of actors from the energy sector:** The financial analysis conducted for existing private households (see Part B) showed that DC will be a good business case for the financer in terms of both capital cost savings and energy savings in the case the building is connected to a DC distribution grid. This indicates that the adoption of DC by grid operators is a significant factor for achieving success in this market.

Stedin (grid operator in the Netherlands) showed its support to the DC-Flexhouse project with a letter of intent, however, representatives of this organization are not actively involved in the project. Project partners should put effort on engaging grid operators. Alliander is the only grid operator at the moment that experiments with DC grids, therefore its involvement is valuable. In any case, the benefit of congestion management is a benefit for grid operators. Therefore, the DC-Flexhouse prototype should be demonstrated to them as well.

6. **Increase awareness:** Future potential customers are not aware of the differences between AC and DC power, key channels to reach the potential customers are not aware of DC technology (construction sector) and electrical installers are not trained to work with DC power. Therefore, at this early stage of technology development proper dissemination is vital for future market success. Dissemination should initially target co-innovators and then the target market. Potential means for dissemination are:

- participation in exhibitions and conferences (PV, battery storage, smart grids)
- use of current contacts with representatives from involved sectors
- involvement of associations to reach a bigger audience (electrical installers, construction companies, suppliers, housing associations)
- organization of workshops (participants from key actor as identified in the DC innovation ecosystems (see Figure 20))

7. **Understand the customers:** In the beginning of this PDEng project, I interviewed members of the DC-Flexhouse project in order to understand the value proposition of DC from their perspective. I asked the interviewees what would convince themselves to invest in such a system. All of them mentioned comfort and aesthetics due to the elimination of power converters of electronics. However, these interviewees could not name a price for such a comfort. This indicates that a better understanding of the market is necessary. Market research helps understand the potential of the technology and what has to be done to meet customers’ needs (price, comfort, performance, efficiency).

When talking with potential customers, project partners should make sure that the value proposition of DC is well-communicated and the customer’s perspective well-understood. This
will help to deeply understand the market, design a system that meets the customer’s needs, and assess the market potential.

Figure 32. The 9x effect. There’s a fundamental problem for companies that want consumers to embrace innovations: While developers are already sold on their products and see them as essential, consumers are reluctant to part with what they have. This conflict results in a mismatch of nine to one between what innovators believe consumers want and what consumers truly desire [29].

8. **Use of appropriate communication strategy**: The communication strategy should reflect the target customer segment. When DC innovation is communicated as a solution that offers a comfortable experience due to the elimination of AC to DC converters, most likely the target customer segment is wealthy people that are willing and able to buy such a system. When integrated smart control is stressed as the competitive advantage of AC, market segments that might be interested are (owners of) buildings where smart control is needed, such as offices and other commercial buildings.

9. **Engage in open innovation**: Instead of using a portfolio of patents as a leverage against the competition, open innovation can be a better strategy to reach the market. Chesbrough defines open innovation as “the use of purposive inflows and outflows of knowledge to accelerate internal innovation, and expand the markets for external use of innovation, respectively. (This paradigm) assumes that firms can and should use external ideas as well as internal ideas, and internal and external paths to markets, as they look to advance their technology” [83]. In other words, open innovation refers to the collaboration between companies, individuals and public institutes to create innovative products and services and share related risks and rewards in the process.

Open innovation suggests that a company should no longer lock up its IP, but instead it should find ways to profit from others’ use of that technology through licensing agreements, joint ventures and other arrangements [84]. Overall, open innovation can:

- reduce costs;
- accelerate time-to-market;
- create new revenue streams for the company that has developed the innovative idea [85];
- minimize innovation risk: it allows a company to expand the “breadth of ideas, opportunities and know-how, while minimizing the technical and market risks associated with the innovation” [86];
- rescue “false negatives”, meaning projects that initially seem to lack promise but turn out to be surprisingly valuable: a company with a closed innovation approach is prone to miss a number of opportunities because many fall outside their organization’s
current business or will need to be combined with external technologies to unlock their potential [84]; and

- help evolve the business model: it propels the company’s business model forward in response to changes in the market place, through external and internal ideas [87].

Tesla Motors is one example of a company that adopted open innovation in order to advance electric vehicle technology. The company’s goals is to accelerate the advent of sustainable transport. According to its CEO, Elon Musk, “laying intellectual property landmines behind us to inhibit others was like acting in a manner contrary to that goal” [88]. Therefore, in order to encourage the competition to enter the electric car market, Tesla Motors opened up its patent portfolio. Beyond the potential economic results, Tesla believes that this move can assist in a transition from fossil fuel consuming products. Therefore, open innovation can be seen as an act of social responsibility. When open-sourced, innovation can help collectively move towards solutions to society’s most pressing issues [89].

Project partners within DC-Flexhouse, who can be seen as representing a small-scale DC innovation ecosystem, can follow the same example and engage in open innovation. As described above, the development of social networks plays a key role in sustainability transitions. Open innovation will most probably contribute to the expansion of the social network and spur competitors to co-innovate. This will lead to a change in one of the dimensions of the sociotechnical regime, the industry structure, which could facilitate eventually a breakthrough of DC innovation at the energy regime.

10. Be aware of wider developments: According to the transition management literature, the transformation of the existing energy regime will start in early niche markets and/or technological niches. The process of the transition to DC can be analyzed through the MLP framework (Figure 3). DC innovation can become influential at the regime level through the interaction between processes at different levels [1]:

a) niche innovations build up internal momentum

b) changes at the landscape level create pressure on the regime

c) destabilization of the regime creates windows of opportunity for niche innovations

Therefore, based on the MLP approach it can be argued that wider developments in the regime and socio-technical landscape (e.g. new regulatory measures to push energy efficiency improvement, environmental awareness, shifts in consumer preferences) determine the commercial success of DC. Actors within the DC innovation ecosystem have to be aware of these developments in order to adapt their strategy accordingly.
Figure 33. Action plan for business development with key areas of attention to reach the vision for DC.
9. Conclusions

As part of the DC-Flexhouse project, this PDEng project aims at assessing the business case of DC in the built environment and providing strategies for the transition to DC grids.

The implementation of DC applications is a radical innovation for both the distribution level and the building level. The energy infrastructure is predominantly powered with AC, manufacturers produce devices based on AC standards and people are using many AC products across a long life span. Therefore, at a first glance it seems that there is no explicit market need and consequently no market for DC. As a result, managers of companies and organizations that have to co-innovate (i.e. manufacturers of DC components) to develop DC applications might easily reject DC as a bad business proposal.

In order to understand how radical sustainable innovations can eventually reach the market, two models from the transition management literature were applied: the Multi-level Perspective (MLP) and the Transition Management (TM). The MLP describes the drivers that lead to the breakthrough of innovations and has been fruitfully applied in studies of transitions to sustainability [1], for example in electricity systems [76], mobility and ‘green’ cars [90], and biogas and co-combustion [21]. The TM model stresses the role of social networks in facilitating and directing processes in the direction of sustainability [22]. In order to influence the current energy infrastructure, effort has to be put on developing formal and informal networks of actors with joint interests and strong commitment. The two models complement each other. MLP describes wider developments that create windows of opportunities for innovations that first appear in niche markets, while TM provides guidelines about how actors with vested interests in an innovation can stimulate niche development in the first place.

Applying these models in this project was indeed useful. They provided a more structured framework for understanding and analyzing the drivers that could open up space for DC technology in the existing energy regime. Additionally, guidelines proposed by these models were used to develop recommendations for turning DC into a commercial success.

According to transition management literature [19] [82] [1], the transformation of regimes starts from technological niches and/or early niche markets. Technological niches are pilot and demonstration projects that are usually financially supported through subsidy schemes (DC-Flexhouse project is part of a technological niche). Early adopters are market segments that have different needs from the mainstream market. In this context, the first step was to identify early adopters groups by combining the value proposition of DC with needs and perceived values in different market segments. Indicatively, in addition to technological niches, potential groups of early adopters are: office buildings with high computing and lighting demand, educational buildings, housing corporations that have signed agreements for improved energy efficiencies (Stroomversnelling) and private households with high income that value comfort or want energy independence.

The wider developments demonstrating the future potential of DC are the increase in the use of DC loads and PV penetration, the need for storage and smart grid applications, the development of regulations for improved energy efficiency (BENG regulation for new constructions), the development of the latest USB standard and the ongoing exploitation of DC grids in developing countries. Overall, it can be argued that these wider development can potentially create windows of opportunities for the DC proposition.

The output of the DC-Flexhouse project will be a first prototype. In order for DC technology to reach the technology readiness level (TRL) for application in buildings, there will be a need for the implementation of more pilot and demonstration projects (growth of technological niches). The time
from technological niches to niche markets and eventually to an established market cannot be predicted at this moment, however it will be accelerated through the development of broad and deep social networks [82].

A financial analysis for the renovation of private households with DC technology shows that a DC micro grid is a good business case for the building owner when the power supply is provided by a DC distribution grid (see Part B). The difference is in the cost of the bidirectional inverter that is necessary in the case of connection to the existing AC grid. In this case the payback period for residential private households is not in favor of DC. This indicates that further research should focus on the economic feasibility of a DC distribution grid. Alliander is the only grid operator in the Netherlands that has shown interest in the exploitation of DC distribution grids. Involving actors within Alliander could be beneficial for both sides.

However, the existence of a DC distribution grid does not determine the success of DC micro grids in the case of new buildings. Labor and other material costs for the electrical installation are already included in the budget of new construction projects. As a result the investment cost for a DC installation is lower than the cost of a similar AC-based system. This indicates that DC can have a potential in the new construction market before entering existing buildings.

Additional financial incentives could be given to building owners through the implementation of smart grid applications that enable flexibility in energy consumption and/or production (DSM, DR). The benefits of flexibility can be translated to grid value and energy market value. The grid value is considered of interest to the grid operators, while the energy market value is considered of interest to the energy suppliers [32]. In order to reach a mature level for large-scale implementation of DC smart grids, further research should be done to investigate how both values can be translated into value for the end-user (building owners/project developer) and clearly define the roles and responsibilities of all future actors within the smart grid markets.

In conclusion, it appears to be difficult to gauge the market growth at these early stages of DC technology development. However, developments in the sociotechnical landscape and regime, such as the increasing use of DC loads, growing penetration of PV, expected falling prices of battery storage technologies and regulations for improved energy efficiency of buildings, point at the future potential of DC. Parties that want to promote DC technology should first target to build strategic alliances with co-innovators and find frontrunners that are willing to invest and adopt the innovation. Niche markets such as new buildings might initially not generate a substantial level of profit for the actors in the value chain, but entering these niche markets now will facilitate broader market development at a later stage.
10. References


Chiang Mai World Green City," in 2015 IEEE First International Conference on DC Microgrids (ICDCM), Atlanta, USA, 2015.


[37] "German Standardization Roadmap," VDE Association for Electrical Electronic and Information, 2016.


[50] A. Schärer, "Efficient DC power supply in data center," ABB Low Voltage Systems, [online], available: https://library.e.abb.com/public/60289ad65efef903c1257c5a0040a37b/16-21%204m412_EN_72dpi.pdf, Lentzburg, Switzerland.


[54] S. Willems and W. Aerts, "Study and simulation of a DC micro grid with focus on efficiency, use of materials and economic constraints".


C. van der Weijde, "CMS Guide to Electricity, the Netherlands".


11. Appendix

11.1 Interviews

The goal of the interview was to identify the strong and weak points of the DC renovation method that is being developed in the framework of the DC-Flexhouse project, from both the technical and the market perspective. This input was used to identify where we stand now, where we want to go and how to go there. At this point, the interviewees were professionals involved in the DC-Flexhouse project. More specifically, the interview sought answers to the following questions:

- **Current situation:**
  What is the current state of development of the DC renovation?

- **Unique Ecosystem’s Value Proposition:**
  What would convince you to change to DC?

- **Opportunities versus Challenges/weaknesses/bottlenecks:**
  What opportunities and bottlenecks are experienced and/or expected?

- **Stakeholders/Actors:**
  Which are the main sectors within the value chain that will influence the transition?

- **Realistic and desirable future scenarios:**
  What is the most realistic and the most desirable future for the energy systems?

- **Market:**
  Who are the most likely end-users/what is the customer segment?

- **Driving forces in favour of DC:**
  What are the external factors/trends that will influence the transition?

**Questions:**

1. **Introductory questions:**
   1.1 What is your role within the DC-Flexhouse project? What is your objective? What is your benefit from the implementation of this project?
   1.2 Are you involved in other projects related to smart DC grids? If yes, which ones.

2. **Current situation:**
   2.1 What is the current state of development of the DC system for renovations?
   2.2 What are the components already developed and by whom?
   2.3 What is still missing in the development (components, equipment, interfaces, safety, hardware and software)?
   2.4 Who is going to develop the missing technology links?
   2.5 Do you have any results from other projects (research or pilot projects)?
   2.6 What is the efficiency gained with DC and under which circumstances (scenarios/configurations, e.g. only when connected to a DC micro grid, only with renewables, etc.)?
   2.7 What other organisations, research institutes, universities conduct research on DC smart grids?

   **Market-related**
   2.8 Is there interest from other companies on DC? If yes, can you name some?
   2.9 What type of products/services do they develop/in what sector do they operate?
3. Unique Ecosystem's Value Proposition:

3.1 What are the benefits of DC power supply compared to AC?
3.2 Are there other benefits of DC irrespective to AC?
3.3 What would convince you to change to DC/What should DC offer to convince you to change your power supply?
3.4 What do you want to offer to the end users?
3.5 Rank the following reasons for DC renovation: efficiency/savings, comfort, smart, environmental consciousness, love for technology, space savings, aesthetics, longer lifetime of appliances, safety, initial cost, maintenance costs)

4. Market:

4.1 Do you think there is a market demand for the DC renovation?
4.2 Identify end-users of the renovation/DC technology/customer segment (household owners (private), housing corporations, economic status, age, background, environmental awareness, awareness on smart grids, tech lovers, etc.)

5. Actors/Stakeholders:

5.1 Who are the main actors, stakeholders of the value chain?
5.2 Who else needs to succeed so that the DC renovation would become successful?
5.3 What other products/components/services from other organisations create synergies with your offerings?

6. Opportunities versus Challenges/weaknesses/bottlenecks:

6.1 What opportunities are offered by the transition to DC for your organisation?
6.2 What opportunities are offered by the transition for actors involved in the value chain?
6.3 What are the challenges of the transition from a technical point of view?
6.4 What are the challenges related to market introduction?

7. Realistic and desirable future scenarios:

7.1 What would be in your opinion the most realistic and the most desirable scenario?
7.2 How do you see the technical feasibility of the DC renovation? The transition from AC to 100% DC?
7.3 What are the logical steps for this transition?
7.4 What is the timescale for all these system changes?

8. Driving forces in favour of DC:

8.1 Who is the driving force for this makeover/transition?
8.2 Will policy makers/government/energy companies (grid operators) influence the transition?
8.3 In case policy makers and grid operators don’t recognise the benefit from this transition, does this risk slowing things down or even blocking them?
8.4 What is your vision for the future in the energy sector (future energy systems?)
11.2 Companies that have already adopted the USB-C standard

The table below lists electronics manufacturers that have already adopted the USB-C standard in their products.

Table 11. List of companies that have already adopted the USB-C standard in their products

<table>
<thead>
<tr>
<th>Company</th>
<th>Product</th>
<th>Product category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>MacBook</td>
<td>laptop</td>
</tr>
<tr>
<td>Google</td>
<td>Chromebook</td>
<td>laptop</td>
</tr>
<tr>
<td>Nokia</td>
<td>N1</td>
<td>tablet</td>
</tr>
<tr>
<td>HTC</td>
<td>HTC 10</td>
<td>smartphone</td>
</tr>
<tr>
<td>LG</td>
<td>G5</td>
<td>smartphone</td>
</tr>
<tr>
<td>OnePlus</td>
<td>OnePlus 2</td>
<td>smartphone</td>
</tr>
<tr>
<td>Google</td>
<td>Nexus 6P, 5X</td>
<td>smartphone</td>
</tr>
<tr>
<td>Samsung</td>
<td>Galaxy Note 7</td>
<td>smartphone</td>
</tr>
<tr>
<td>Asus</td>
<td>ZenPad S80</td>
<td>tablet</td>
</tr>
<tr>
<td>Lenovo</td>
<td>Yoga 900</td>
<td>laptop</td>
</tr>
<tr>
<td>HP</td>
<td>Spectre 13</td>
<td>laptop</td>
</tr>
<tr>
<td>Dell</td>
<td>XPS 13</td>
<td>Laptop</td>
</tr>
</tbody>
</table>
Part B: Case study for residential buildings
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1. Introduction

This chapter investigates the business case of DC for the building owner (private households) who is the financer of the DC renovation. The investigation of the business case for the building owner serves to validate the value proposition of DC for the specific market segment and to consequently assess the market potential in this specific segment. In other words, the success of the set of DC products in the market depends on the creation of value for the potential financer.

The business case for the building owner is assessed via a cost-benefit analysis. DC installations are compared to similar AC installations in terms of energy savings and capital costs. The following sections discuss the energy savings achieved by shifting to DC and how these are translated to profit gains for the building owner, as well as the investment costs for the installations for both AC- and DC-based systems. Finally, this data is used to perform a financial analysis in order to investigate the economic feasibility of the in-building DC installation from the perspective of the building owner. It should be noted that there are also qualitative aspects that cannot be directly translated into financial benefits, but add value to the DC proposition.

2. Energy savings

The direct use of DC can lead to energy savings at the building level due to the elimination of the AC to DC, or DC to AC to DC (for a PV installation) conversion steps. The majority of studies that address DC power systems in the context of energy savings have been analytical rather than experimental in nature. There are only a few pilot projects for the built environment with experimental findings and therefore most of the studies are based on assumptions regarding improved efficiencies of DC-DC power converters and DC loads.

In addition, residential loads have poor coincidence with PV system output and are less predictable. In the absence of energy storage and smart control, only loads coincident with PV system output can benefit from direct DC distribution. Therefore, it can be assumed that the real potential of DC in the residential sector in terms of energy savings lies in the integration of storage. If handled properly, a battery storage system can buffer electricity and reduce the mismatch between PV generation and load [1].

Vossos et al. [2] examined the potential of energy savings for all-DC households with and without storage. The chosen voltages for the DC-household reflect existing (24VDC) and pending (380VDC) EMerge Alliance standards for DC distribution, while connection to AC distribution is considered. The assumptions for power system conversion efficiencies are shown in Table 12.

According to their model, it is predicted that the direct use of DC will save energy with respect to conventional AC distribution and that the savings for the battery-integrated systems are more than twice that of non-storage systems. DC saves around 5% and 13% of total electricity consumption without and with storage, respectively (Table 14). This model addresses only the energy savings achieved by distributing DC power to DC loads and eliminating the conversion steps. According to the same study, additional energy savings can be obtained by switching existing appliances to efficient DC-internal appliances (overall 33% appliance efficiency savings). However, these savings are excluded from the simulation model.
Table 12. Power system full-load conversion efficiencies from [2]

<table>
<thead>
<tr>
<th>Power system component</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-house PV Inverter, includes MPPT(^a)</td>
<td>95</td>
</tr>
<tr>
<td>DC-house rectifier (meter→DC)(^b)</td>
<td>93</td>
</tr>
<tr>
<td>DC-house inverter (DC→meter)(^c)</td>
<td>97</td>
</tr>
<tr>
<td>Charge controller or MPPT (DC–DC converter)(^d)</td>
<td>98</td>
</tr>
<tr>
<td>DC-house DC–DC load converter: 380 V–24V(^b)</td>
<td>95</td>
</tr>
<tr>
<td>Battery</td>
<td>90</td>
</tr>
</tbody>
</table>

\(^a\) Typical of today’s new PV-system string inverters.
\(^b\) Represents best models that could be built today, according to industry experts interviewed
\(^c\) Today’s PV-system inverter minus the MPPT, which has estimated losses of 2%.
\(^d\) Typical of today’s high-end charge controller efficiencies.
Another study examines the potential DC energy savings for an all-DC household in the cases it is connected to AC and DC distribution [3] (Figure 36). The chosen voltage for the DC-household is in line with the pending IEC standard (350VDC, the same as applied in the DC-Flexhouse project). The assumptions about power system efficiencies in this model are shown in Table 13.

![DC architecture with PV and storage (connection to DC distribution grid)](image)

According to this study, DC can save up to 8% of the total electricity consumption when the household is connected to a DC distribution grid, while this figure drops to 5% when connected to a conventional AC grid. Both cases do not consider storage. However, energy savings for the latter case (connection to AC distribution grid) can increase to 8% when load shifting to match PV energy generation is applied.

Table 13. Power system conversion efficiencies from [3]

<table>
<thead>
<tr>
<th>Power system component</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-house PV Inverter, includes MPPT</td>
<td>91,8</td>
</tr>
<tr>
<td>AC-DC bidirectional converter</td>
<td>98</td>
</tr>
<tr>
<td>Charge controller or MPPT (DC-DC converter)</td>
<td>98</td>
</tr>
<tr>
<td>AC-house AC-DC converter for household loads</td>
<td>87</td>
</tr>
<tr>
<td>DC-house DC–DC load converter</td>
<td>90</td>
</tr>
<tr>
<td>AC-house LED driver</td>
<td>85</td>
</tr>
<tr>
<td>DC-house LED driver</td>
<td>90</td>
</tr>
</tbody>
</table>

It can be seen that the estimated energy savings for non-storage systems connected to AC distribution grids are the same for both studies (5%) although chosen voltage levels and simulation modelling are different. Based on the first study examined, energy savings in the DC case can increase by 160% when storage is integrated for connection to an AC grid. This increase is due to lower DC to AC conversion losses in the bidirectional household converter (household connection to grid), lower conversion losses from power distribution to loads and better exploitation of DC PV power output (electricity buffering). If the same percent increase is considered for the case of connection to DC distribution, energy savings from DC can rise to 20% of the total energy consumption when storage is integrated.

Considering that a typical electricity consumption for a household in the Netherlands is around 3500 kWh/year [4] and a 0,18 €/kWh [5] electricity cost, the DC energy savings and respective cost savings are shown in the table below:
Table 14. DC energy savings and respective cost savings

<table>
<thead>
<tr>
<th>DC savings as percentage of total AC household load (%)</th>
<th>Connection to AC distribution grid</th>
<th>Connection to DC distribution grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-storage</td>
<td>Storage</td>
<td>Non-storage</td>
</tr>
<tr>
<td>DC energy savings (kWh/year)</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>DC cost savings (€/year)</td>
<td>175</td>
<td>455</td>
</tr>
</tbody>
</table>

Figure 37. DC savings as percentage of total AC household load

Sensitivity analysis

Based on previous studies on DC power systems [2] [3], it can be concluded that energy savings of DC distribution are highly dependent on:

- power system efficiencies;
- energy consumption profile of the user;
- load type;
- PV system and storage capacity;
- distribution voltage; and
- whether the household grid is connected to an AC or a DC distribution system.

Therefore, a more accurate estimation of energy savings requires the availability of experimental data about system efficiencies and a detailed study for each individual building project.

It should also be taken into account that the estimation of DC energy savings depends on the efficiencies of AC-DC power converters. If the appliance AC-DC conversion efficiencies improve, energy savings from direct DC distribution decrease, and therefore, the business case for the building owner changes.
3. Investment costs

In order to assess the cost-effectiveness of DC for the end-user (building owner), DC is compared to a reference AC installation in terms of required capital cost for 4 scenarios:

4. Connection to an AC grid without storage
5. Connection to a DC grid without storage
6. Connection to an AC grid with storage (both AC- and DC-coupled battery systems are considered for the reference AC installation)
7. Connection to a DC grid with storage (both AC- and DC-coupled battery systems are considered for the reference AC installation)

For each of these scenarios, DC is compared to the respective AC-based installation (with and without storage). In addition, both AC and DC-coupled battery systems are considered for the AC-based installations\(^1\) (Figure 38).

---

\(^1\) The term coupling refers to the point of connection. In a DC-coupled system, batteries are connected to the DC side of the PV system, while in AC-coupled systems the point of connection is on the AC side.
Figure 38. Differences between AC-coupled and DC-coupled PV battery systems. In the AC-coupled system, the battery can also store energy from the grid. In the DC-coupled system, only energy produced by the PV installation can be stored, unless the inverter is bi-directional.

The components and respective numbers and prices for the DC-household and the AC-household are shown in Table 15 and Table 16, respectively (see also Figure 34, Figure 35 and Figure 36 for the differences in the system architectures).

Table 15. Capital costs for the DC renovation of a household with a PV and a battery storage system

<table>
<thead>
<tr>
<th>Costs in a DC grid</th>
<th>No</th>
<th>Price (€/unit)</th>
<th>Total (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution box</td>
<td>1</td>
<td>700,00</td>
<td>700,00</td>
</tr>
<tr>
<td>Other materials (wiring, switches, connection points)</td>
<td>n/a</td>
<td>1000,00</td>
<td>1000,00</td>
</tr>
<tr>
<td>USB-C wall sockets (^2)</td>
<td>10</td>
<td>50,00</td>
<td>500,00</td>
</tr>
<tr>
<td>DC LED drivers</td>
<td>8</td>
<td>2,52</td>
<td>20,16</td>
</tr>
<tr>
<td>Bi-directional AC-DC converter</td>
<td>1</td>
<td>3000,00</td>
<td>3000,00</td>
</tr>
<tr>
<td>MPPT (^3)</td>
<td>1</td>
<td>1000,00</td>
<td>1000,00</td>
</tr>
<tr>
<td>Battery charge controller (^7)</td>
<td>1</td>
<td>750,00</td>
<td>750,00</td>
</tr>
<tr>
<td>Change of devices to DC</td>
<td>8</td>
<td>80,00</td>
<td>640,00</td>
</tr>
<tr>
<td>Installation costs</td>
<td>n/a</td>
<td>1870,00</td>
<td>1870,00</td>
</tr>
</tbody>
</table>

\(^2\) The USB-C wall sockets can power electronic devices up to 100 W without need for additional converters.

\(^3\) The MPPT includes the DC-DC converter for the connection of the PV installation to the DC bus.
Table 16. Capital costs of an AC household with a PV and a battery storage system

<table>
<thead>
<tr>
<th>Costs in an AC grid</th>
<th>No</th>
<th>Price (€/unit)</th>
<th>Total (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-DC converters for electronics [8] [9]</td>
<td>8</td>
<td>35,00</td>
<td>280,00</td>
</tr>
<tr>
<td>AC LED driver [10]</td>
<td>8</td>
<td>2,80</td>
<td>22,40</td>
</tr>
<tr>
<td>Solar inverter including MPPT [11]</td>
<td>1</td>
<td>2700,00</td>
<td>2700,00</td>
</tr>
<tr>
<td>Battery charge controller [12]</td>
<td>1</td>
<td>2500,00</td>
<td>2500,00</td>
</tr>
<tr>
<td>Battery charge controller [7]</td>
<td>1</td>
<td>750,00</td>
<td>750,00</td>
</tr>
</tbody>
</table>

The costs for the components in the DC grid is rather an estimation than an actual sales price because the technology is still under development. The cost of the distribution box and the USB-C wall socket is based on input from DC-Flexhouse project partners. For the LED drivers, a 10% reduction in cost is assumed due to the removal of the AC to DC conversion step. For the PV system the DC-DC converter is integrated in the Maximum Power Point Tracker (MPPT). It is also assumed that 8 household devices (other than electronics) are configured to work with DC power. The cost of changing these devices is again an estimation, because at the time this study is conducted actual data are not available.

The figures for the AC grid are based on existing products. The solar inverter is a SMA Sunny Boy 8000TL, the battery charge controller is a SMA Sunny Island, and the LED Driver is the Xitanium Philips LED driver 25W. The cost of AC to DC converters for electronics is an average estimation from USB-C chargers available on the market. Solar panels, storage and respective installation costs exist in both AC- and DC-worlds, therefore the cost of these components is excluded.

For scenarios 3 and 4 there is also need for a home energy management system (EMS). In the envisioned DC-world, the controller for individual loads is integrated in the load, while there is a need for an additional controller that communicates and controls loads based on the available power. This controller is not yet developed, therefore the considered price is an assumption. For the DC-household it is assumed that the cost of the controller is included in the cost of changing the device to operate on DC power (indicated as change of devices to DC in Table 15).

In the AC-world, there is a wide variety of technologies and products provided by different vendors. The chosen components for the AC-household in this study are provided by SMA because it offers a whole-home energy management solution (SMA Sunny home manager) and the prices of the components are available online.

Table 17. Capital costs of energy management systems in an AC and DC household

<table>
<thead>
<tr>
<th>Energy management systems</th>
<th>No</th>
<th>Price (€/unit)</th>
<th>Total (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC household</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central controller [13] [14]</td>
<td>1</td>
<td>382,00</td>
<td>382,00</td>
</tr>
<tr>
<td>Smart plugs [13] [14]</td>
<td>8</td>
<td>120,00</td>
<td>960,00</td>
</tr>
<tr>
<td>Installation</td>
<td>n/a</td>
<td>500,00</td>
<td>500,00</td>
</tr>
<tr>
<td>DC household</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central controller</td>
<td>1</td>
<td>300,00</td>
<td>300,00</td>
</tr>
</tbody>
</table>

4 For AC-coupled battery systems.
5 For DC-coupled battery systems.
\section{Non-storage systems}

The tables below show the additional capital of the DC household relative to a conventional AC household for scenarios 1 (connection to AC distribution grid) and 2 (connection to DC distribution grid).

Table 18. Additional capital costs for scenario 1: non-storage, connection to AC distribution grid

<table>
<thead>
<tr>
<th></th>
<th>AC grid</th>
<th>DC grid</th>
<th>Additional capital</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution box</td>
<td>-</td>
<td>€ 700,00</td>
<td>€ 700,00</td>
</tr>
<tr>
<td>Other materials (wiring, switches, connection points)</td>
<td>-</td>
<td>€ 1.000,00</td>
<td>€ 1.000,00</td>
</tr>
<tr>
<td>Power delivery to DC loads(^6)</td>
<td>€ 280,00</td>
<td>€ 500,00</td>
<td>€ 220,00</td>
</tr>
<tr>
<td>LED drivers</td>
<td>€ 22,40</td>
<td>€ 20,16</td>
<td>€ -2,24</td>
</tr>
<tr>
<td>Change of devices to DC</td>
<td>-</td>
<td>€ 640,00</td>
<td>€ 640,00</td>
</tr>
<tr>
<td>Bi-directional AC to DC</td>
<td>-</td>
<td>€ 3.000,00</td>
<td>€ 3.000,00</td>
</tr>
<tr>
<td>Installation</td>
<td>-</td>
<td>€ 1.870,00</td>
<td>€ 1.870,00</td>
</tr>
<tr>
<td>Integration of PV(^7)</td>
<td>€ 2.700,00</td>
<td>€ 1.000,00</td>
<td>€ -1.700,00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>€ 3.002,40</td>
<td>€ 8.730,16</td>
<td>€ 5.727,76</td>
</tr>
</tbody>
</table>

Table 19. Additional capital costs for scenario 2: non-storage, connection to DC distribution grid

<table>
<thead>
<tr>
<th></th>
<th>AC grid</th>
<th>DC grid</th>
<th>Additional capital</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution box</td>
<td>-</td>
<td>€ 700,00</td>
<td>€ 700,00</td>
</tr>
<tr>
<td>Other materials (wiring, switches, connection points)</td>
<td>-</td>
<td>€ 1.000,00</td>
<td>€ 1.000,00</td>
</tr>
<tr>
<td>Power delivery to DC loads(^6)</td>
<td>€ 280,00</td>
<td>€ 500,00</td>
<td>€ 220,00</td>
</tr>
<tr>
<td>LED drivers</td>
<td>€ 22,40</td>
<td>€ 20,16</td>
<td>€ -2,24</td>
</tr>
<tr>
<td>Change of devices to DC</td>
<td>-</td>
<td>€ 640,00</td>
<td>€ 640,00</td>
</tr>
<tr>
<td>Installation</td>
<td>-</td>
<td>€ 1.870,00</td>
<td>€ 1.870,00</td>
</tr>
<tr>
<td>Integration of PV(^7)</td>
<td>€ 2.700,00</td>
<td>€ 1.000,00</td>
<td>€ -1.700,00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>€ 3.002,40</td>
<td>€ 5.730,16</td>
<td>€ 2.727,76</td>
</tr>
</tbody>
</table>

\(^6\) In the DC-world, electronic devices that use the USB-C standard can be directly plugged into the USB-wall sockets without the need for power converters. The power converter is integrated in the socket. In order for the end-user to benefit from avoiding the cost of power adapters, manufacturers of electronics have to agree to sell the devices and the converters separately.

\(^7\) In the AC-world there is need for a solar inverter which includes a MPPT. In the DC-world the PV is connected to the DC bus via only the MPPT (the DC-DC converter is integrated in the MPPT).
b. DC-coupled battery systems

In the case of a DC-coupled battery system in the AC household, the battery is connected to the DC side of the electrical wiring with a DC-DC charge controller (see Figure 38). In DC-coupled systems, the battery can store only energy produced by the PV system and not energy from the grid, unless the solar inverter is bi-directional.

The following tables present a comparison between an AC and a DC household in terms of capital investment for scenarios 3 and 4 considering a DC-coupled battery system as the reference design.

Table 20. Additional capital costs for scenario 3: storage, connection to AC distribution grid (in the AC household, the battery system is DC-coupled)

<table>
<thead>
<tr>
<th></th>
<th>AC grid</th>
<th>DC grid</th>
<th>Additional capital</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution box</td>
<td>-</td>
<td>€ 700,00</td>
<td>€ 700,00</td>
</tr>
<tr>
<td>Other materials (wiring, switches, connection points)</td>
<td>-</td>
<td>€ 1,000,00</td>
<td>€ 1,000,00</td>
</tr>
<tr>
<td>Power delivery to DC loads(^6)</td>
<td>€ 280,00</td>
<td>€ 500,00</td>
<td>€ 220,00</td>
</tr>
<tr>
<td>LED drivers</td>
<td>€ 22,40</td>
<td>€ 20,16</td>
<td>€ -2,24</td>
</tr>
<tr>
<td>Change of devices to DC</td>
<td>-</td>
<td>€ 640,00</td>
<td>€ 640,00</td>
</tr>
<tr>
<td>Bi-directional AC to DC converter</td>
<td>-</td>
<td>€ 3,000,00</td>
<td>€ 3,000,00</td>
</tr>
<tr>
<td>Installation</td>
<td>-</td>
<td>€ 1,870,00</td>
<td>€ 1,870,00</td>
</tr>
<tr>
<td>Integration of PV(^7)</td>
<td>€ 2,700,00</td>
<td>€ 1,000,00</td>
<td>€ -1,700,00</td>
</tr>
<tr>
<td>EMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central controller</td>
<td>€ 382,00</td>
<td>€ 300,00</td>
<td>€ -82,00</td>
</tr>
<tr>
<td>Smart plugs</td>
<td>€ 960,00</td>
<td>-</td>
<td>€ -960,00</td>
</tr>
<tr>
<td>Installation</td>
<td>€ 500,00</td>
<td>-</td>
<td>€ -500,00</td>
</tr>
<tr>
<td>Total</td>
<td>€ 4,844,40</td>
<td>€ 9,030,16</td>
<td>€ 4,185,76</td>
</tr>
</tbody>
</table>

Table 21. Additional capital costs for scenario 4: storage, connection to DC distribution grid (in the AC household, the battery system is DC-coupled)

<table>
<thead>
<tr>
<th></th>
<th>AC grid</th>
<th>DC grid</th>
<th>Additional capital</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution box</td>
<td>-</td>
<td>€ 700,00</td>
<td>€ 700,00</td>
</tr>
<tr>
<td>Other materials (wiring, switches, connection points)</td>
<td>-</td>
<td>€ 1,000,00</td>
<td>€ 1,000,00</td>
</tr>
<tr>
<td>Power delivery to DC loads(^6)</td>
<td>€ 280,00</td>
<td>€ 500,00</td>
<td>€ 220,00</td>
</tr>
<tr>
<td>LED drivers</td>
<td>€ 22,40</td>
<td>€ 20,16</td>
<td>€ -2,24</td>
</tr>
<tr>
<td>Change of devices to DC</td>
<td>-</td>
<td>€ 640,00</td>
<td>€ 640,00</td>
</tr>
<tr>
<td>Installation</td>
<td>-</td>
<td>€ 1,870,00</td>
<td>€ 1,870,00</td>
</tr>
<tr>
<td>Integration of PV(^7)</td>
<td>€ 2,700,00</td>
<td>€ 1,000,00</td>
<td>€ -1,700,00</td>
</tr>
<tr>
<td>EMS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central controller</td>
<td>€ 382,00</td>
<td>€ 300,00</td>
<td>€ -82,00</td>
</tr>
<tr>
<td>Smart plugs</td>
<td>€ 960,00</td>
<td>-</td>
<td>€ -960,00</td>
</tr>
<tr>
<td>Installation</td>
<td>€ 500,00</td>
<td>-</td>
<td>€ -500,00</td>
</tr>
<tr>
<td>Total</td>
<td>€ 4,844,40</td>
<td>€ 6,030,16</td>
<td>€ 1,185,76</td>
</tr>
</tbody>
</table>
c. AC-coupled battery systems

AC-coupling is assumed here (see Figure 38), therefore both a battery inverter and a DC-DC regulator are necessary. The following tables present the difference in necessary capital for an AC and a DC household for scenarios 3 and 4, considering AC-coupled battery system for the AC-based system.

Table 22. Additional capital costs for scenario 3: storage, connection to AC distribution grid (in the AC household, the battery system is AC-coupled)

<table>
<thead>
<tr>
<th></th>
<th>AC grid</th>
<th>DC grid</th>
<th>Additional capital</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution box</td>
<td>-</td>
<td>€ 700,00</td>
<td>€ 700,00</td>
</tr>
<tr>
<td>Other materials (wiring, switches, connection points)</td>
<td>-</td>
<td>€ 1.000,00</td>
<td>€ 1.000,00</td>
</tr>
<tr>
<td>Power delivery to DC loads</td>
<td>€ 280,00</td>
<td>€ 500,00</td>
<td>€ 220,00</td>
</tr>
<tr>
<td>LED drivers</td>
<td>€ 22,40</td>
<td>€ 20,16</td>
<td>€ -2,24</td>
</tr>
<tr>
<td>Change of devices to DC</td>
<td>-</td>
<td>€ 640,00</td>
<td>€ 640,00</td>
</tr>
<tr>
<td>Bidirectional AC to DC converter</td>
<td>-</td>
<td>€ 3.000,00</td>
<td>€ 3.000,00</td>
</tr>
<tr>
<td>Installation</td>
<td>-</td>
<td>€ 1.870,00</td>
<td>€ 1.870,00</td>
</tr>
<tr>
<td>Integration of PV</td>
<td>€ 2.700,00</td>
<td>€ 1.000,00</td>
<td>€ -1.700,00</td>
</tr>
<tr>
<td>Integration of battery storage</td>
<td>€ 2.500,00</td>
<td>€ 750,00</td>
<td>€ -1.750,00</td>
</tr>
<tr>
<td><strong>EMS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central controller</td>
<td>€ 382,00</td>
<td>€ 300,00</td>
<td>€ -82,00</td>
</tr>
<tr>
<td>Smart plugs</td>
<td>€ 960,00</td>
<td>-</td>
<td>€ -960,00</td>
</tr>
<tr>
<td>Installation</td>
<td>€ 500,00</td>
<td>-</td>
<td>€ -500,00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>€ 7.344,40</td>
<td>€ 9.780,16</td>
<td>€ 2.435,76</td>
</tr>
</tbody>
</table>

Table 23. Additional capital costs for scenario 4: storage, connection to DC distribution grid (in the AC household, the battery system is AC-coupled)

<table>
<thead>
<tr>
<th></th>
<th>AC grid</th>
<th>DC grid</th>
<th>Additional capital</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution box</td>
<td>-</td>
<td>€ 700,00</td>
<td>€ 700,00</td>
</tr>
<tr>
<td>Other materials (wiring, switches, connection points)</td>
<td>-</td>
<td>€ 1.000,00</td>
<td>€ 1.000,00</td>
</tr>
<tr>
<td>Power delivery to DC loads</td>
<td>€ 280,00</td>
<td>€ 500,00</td>
<td>€ 220,00</td>
</tr>
<tr>
<td>LED drivers</td>
<td>€ 22,40</td>
<td>€ 20,16</td>
<td>€ -2,24</td>
</tr>
<tr>
<td>Change of devices to DC</td>
<td>-</td>
<td>€ 640,00</td>
<td>€ 640,00</td>
</tr>
<tr>
<td>Bidirectional AC to DC converter</td>
<td>-</td>
<td>€ 3.000,00</td>
<td>€ 3.000,00</td>
</tr>
<tr>
<td>Installation</td>
<td>-</td>
<td>€ 1.870,00</td>
<td>€ 1.870,00</td>
</tr>
<tr>
<td>Integration of PV</td>
<td>€ 2.700,00</td>
<td>€ 1.000,00</td>
<td>€ -1.700,00</td>
</tr>
<tr>
<td>Integration of battery storage</td>
<td>€ 2.500,00</td>
<td>€ 750,00</td>
<td>€ -1.750,00</td>
</tr>
<tr>
<td><strong>EMS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Central controller</td>
<td>€ 382,00</td>
<td>€ 300,00</td>
<td>€ -82,00</td>
</tr>
<tr>
<td>Smart plugs</td>
<td>€ 960,00</td>
<td>-</td>
<td>€ -960,00</td>
</tr>
<tr>
<td>Installation</td>
<td>€ 500,00</td>
<td>-</td>
<td>€ -500,00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>€ 7.344,40</td>
<td>€ 6.780,16</td>
<td>€ -564,24</td>
</tr>
</tbody>
</table>

The analysis of AC and DC installations shows that specifically in the case of existence of a DC distribution grid, the capital cost of a solar system combined with storage is 8% lower for a DC-based system. Therefore, in this case the DC systems offers lower capital costs in combination with energy savings.
8. Financial analysis

Based on the potential energy savings from shifting to DC power systems and the estimated additional required capital, a cost-benefit analysis (CBA) is conducted to assess whether DC constitutes a good business case for residential consumers. The Net Present Value (NPV) and the payback period of the investment are calculated for the 4 scenarios as presented above. Costs refer to the additional required capital to change to a DC distribution system and benefits are the cost savings due to energy savings achieved by shifting to DC.

The NPV calculation does not apply in scenario 4 where a DC installation with PVs and battery storage is compared to a conventional AC installation with an AC-coupled battery system, because the initial capital cost is already lower for the DC installation (see Table 23). In this scenario, DC constitutes a better solution for the integration of PV and battery storage based on the assumptions for costs as presented above.

Net Present Value

The NPV takes into consideration the time value of money. The value of money today is different from the value of the same amount in the future because of earnings that could potentially be made using the money during the intervening time and because of inflation. The NPV is calculated according to the following equation:

\[ NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} \]

In this equation, \( C \) represents the yearly net cash flows (revenues due to electricity savings) and \( r \) the interest rate (also known as discount rate). In other words, the NPV is calculated by discounting all cash flows to the year of investment and then adding them up.

It should be noted that gauging the investment’s profitability with NPV relies on multiple assumptions and estimates, therefore there can be substantial room for error. Estimated factors and assumptions include:

- actual investment costs: The actual difference in additional capital between the AC and DC grid depends on the actual sales price of DC components and the price of AC technologies at the time DC penetrates the market.
- discount rate: The discount rate relies on market forces.
- projected returns: The actual returns depend on the electricity prices in the future and actual system performance.

For example, if the actual level of energy savings is less than 20% based on measurements from the DC-Flexhouse project, the business case for the buyer of the system changes which in turn leads to a different business case for the DC innovation ecosystem.

Market values

The calculation of the discount rate takes into account the market interest rate (i) and the inflation (p) based on the following formula:

\[ r = \frac{1+i}{1+p} - 1 \]

The market interest rate and the inflation in the Netherlands at the moment this study is conducted are 0% [15] and 0.1% [16] respectively.
The figure below shows the NPV calculation for the 4 scenarios for a 25-year period.

The capital cost of the DC-based system is lower than the capital cost of the AC-based system.

Figure 39. NPV calculation for the 4 scenarios
Non-monetary values

In addition to the financial benefits when shifting to DC, there are other advantages that cannot directly be translated to money. These are:

- **Longer life expectancy of appliances:** AC to DC converters include electrolytic capacitors which have a low lifespan. DC to DC converters do not need these elements and, therefore, the lifespan of appliances can be extended [17]. However, due to lack of DC-based grids at the moment this study is conducted, specific projections regarding the increase in lifespan cannot be provided.

- **Convenience and aesthetics:** The distribution of DC power to DC allows users to get rid of all various adapters they use to power their electronic devices.

- **Reduction of weight and space requirements:** In the DC-world, users will not have to carry heavy laptop adapters, while DC enables space savings because of fewer or smaller components. In addition, potentially smaller converters (due to the absence of DC to AC conversion) will facilitate the integration of renewables and storage.

- **Easier implementation of smart grid applications:** DC allows for high penetration of intelligent hardware thanks to electronic transducer technology. It is easier to convert appliances into smart devices because the controller is already integrated in the device.
9. Discussion

This study reveals that an in-building DC installation is only beneficial for the building owner when battery storage is integrated and the power supply of the house is provided by a DC distribution grid. The connection to a conventional AC distribution grid increases the capital cost of the DC installation by the cost of the bi-directional converter, thus negatively affecting the business case of DC from the perspective of the building owner.

Therefore, the success of the DC micro grid in the existing buildings market depends on the economic feasibility of a DC distribution grid. Further research is needed to assess whether DC constitutes a good business case for the distribution level.

In the case of existence of a DC distribution grid, the cost of the DC installation with PVs and battery storage is 8% lower than the cost of the same conventional AC installation when the reference AC installation includes an AC-coupled battery system.

This does not apply if the reference AC installation includes a DC-coupled battery system. In the latter case, the capital cost of the DC system is higher and the payback period quite long (around 10 years) (Figure 39). However, AC-coupled battery systems are most commonly used for grid-tied applications because they offer the possibility to store energy from the grid in addition to the energy produced by the PV array.

However, the existence of a DC distribution grid does not determine the success of DC micro grids in the case of new buildings. Labor and other material costs for the electrical installation are already included in the budget of new construction projects. As a result the investment cost for a DC installation is lowered by 6% compared to a same system that is based on AC power (AC-coupled battery system) (Table 24). This indicates that DC can have a potential in the new construction market even in the absence of a DC distribution grid.

| Table 24. Overview of capital costs of DC and AC installations for new residential buildings with PV and battery systems in the case of connection to a conventional AC distribution grid. The reference AC system has an AC-coupled battery system. Material and installation costs are excluded since they are already included in the budget of new building constructions. Cost savings can be around 9% when the building owner chooses a DC in-building installation. |
|---------------------------------|-----------------|-----------------|-----------------|
| Distribution box                | € 700,00        | € 700,00        | Additional capital |
| Other materials (wiring, switches, connection points) | - | - | - |
| Power delivery to DC loads      | € 280,00        | € 500,00        | € 220,00        |
| LED drivers                     | € 22,40         | € 20,16         | € -2,24         |
| Change of devices to DC         | -               | € 640,00        | € 640,00        |
| Bidirectional AC to DC converter| -               | € 3.000,00      | € 3.000,00      |
| Installation                    | -               | -               | -               |
| Integration of PV               | € 2.700,00      | € 1.000,00      | € -1.700,00     |
| Integration of battery storage  | € 2.500,00      | € 750,00        | € -1.750,00     |
| EMS                             | € 382,00        | € 300,00        | € -82,00        |
| Central controller              | € 960,00        | -               | € -960,00       |
| Smart plugs                     | € 500,00        | -               | € -500,00       |
| Total                           | € 7.344,40      | € 6.910,16      | € -434,24       |
With the existence of a DC distribution grid the capital cost of the DC-based installation is almost half the capital cost of the AC-based installation for new residential buildings (Table 25). This indicates that in the presence of a DC distribution grid, PV and battery systems become more attractive compared to the current situation for new buildings within the residential market.

Table 25. Overview of capital costs of DC and AC installations for new residential buildings with PV and battery systems in the case of connection to a DC distribution grid. The reference AC system has an AC-coupled battery system. Material and installation costs are excluded since they are already included in the budget of new building constructions. Cost savings can be around 45% when the building owner chooses a DC in-building installation.

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10. References


