Update on DC voltage

December 2020

by Rutger Bianchi, Thijs Verboom and Liesbeth van Klink

This report has been commissioned by RVO at the request of TKI Urban Energy

Translated by
Metamorfose Vertalingen

Berenschot
TKI URBAN ENERGY Topsector Energie
Rijksdienst voor Ondernemend Nederland
Stichting Gelijkspanning Nederland

Inhoud

Update on DC voltage

by Rutger Bianchi, Thijs Verboon and Liesbeth van Klink

December 2020

This report has been compiled by Berenschot and commissioned by RVO at the request of TKI Urban Energy Stichting Gelijkspanning Nederland (SGSN) was closely involved in its development.

About TKI Urban Energy and the Netherlands Enterprise Agency (RVO)

TKI Urban Energy is part of Topsector Energie. The organisation encourages companies, knowledge institutions, social organisations and authorities to collaborate on energy innovations. The Netherlands Enterprise Agency (RVO) is a governmental organisation focused on the entrepreneurial climate in the Netherlands. Dutch enterprises can contact the RVO with any questions that they may have on sustainable, agricultural, innovative and international enterprise.

TKI Urban Energy and RVO are jointly promoting research and investigation into energy innovations for a rapid transition to a sustainable, reliable and affordable energy system in the built environment and infrastructure by providing financial support for initiatives, bringing interested parties together and sharing knowledge. Doing this will allow them to strengthen the economic competitiveness of those Dutch businesses and knowledge institutions involved.

Do you have innovative ambitions in flexibility? TKI Urban Energy or RVO may be able support you in your ambitions. The employees at TKI Urban Energy are ready to assess your ideas and help you to find cooperation partners and set up a consortium.

You can contact RVO to find out whether your ideas are eligible for a subsidy (co-financing) from Topsector Energie.

To contact RVO or TKI Urban Energy about these white papers, please contact:

Maarten de Vries
Programme Manager for Smart Energy Systems
+31(0) 616836490, maarten@tki-urbanenergy.nl
www.tki-urbanenergy.nl

Nicole Kerkhof-Damen
Senior Advisor for Smart Energy Systems
+31(0) 627239645, nicole.kerkhof@RVO.nl
www.rvo.nl

About Stichting Gelijkspanning Nederland

Stichting Gelijkspanning Nederland (SGSN) is convinced that DC voltage can make a meaningful contribution to the energy transition, ultimately resulting in a carbon-free society. SGSN does this by amassing and disseminating information on DC voltage. This is achieved through initiation of and participation in projects. SGSN actively endeavours to make the lessons learned from projects available to everyone. If you have expertise or require knowledge on DC voltage, maybe we can help one another. Please get in touch.

Pepijn van Willigenburg
Chairman of the SGSN Board
+31(0) 648279102
Pepijn.van.willigenburg@gelijkspanning.org

Berenschot

TKI URBAN ENERGY
Topsector Energie

Rijksdienst voor Ondernemend Nederland

Stichting Gelijkspanning Nederland

1 Background

AC voltage has formed the basis for our electricity system for more than a century. When it was first chosen, the state of technology was different, plus there was a different combination of electricity consumers and production. At that time, it was a logical choice in view of electricity generation, transport and consumption. Since then, our energy system has changed considerably and there is now a transition underway from centralised to decentralised generation. Consequently, we now have an increasing number of DC voltage technologies, including batteries and PV panels. In addition, there are new innovations in the field of power electronics and many of the barriers to the safe use of DC voltage have disappeared or are easier to address.

These developments now mean that DC voltage offers a new perspective for maintaining electricity flows more efficiently and with less equipment. This is why TKI Urban Energy and the Netherlands Enterprise Agency (RVO) commissioned the DC Voltage Roadmap in 2018. The Roadmap outlines the potential role of DC voltage in a number of market segments. In view of the developments in these market segments over recent years, the Roadmap now needs to be updated. This report looks at the state of affairs in the field of DC voltage in the Netherlands, the differences between DC and AC voltage, changes in the energy system and the benefits and drawbacks of DC voltage.

This report focuses on DC voltage in the Netherlands in general. Additionally, there are also five white papers, each of which looks at a specific market segment in which DC voltage is currently being developed. The white papers go into greater detail on the application of DC voltage and its benefits in these market segments. There is also an overview of projects and an inventory of the difficulties and recommendations for stimulating the adoption of DC voltage within that market segment.

The following market segments are covered:
- Residential and non-residential buildings
- Greenhouse horticulture
- Charging infrastructure
- Public lighting grids
- Local DC voltage grids

Guide

This document contains background information on the application and development of DC voltage in general. Section 2 looks at the differences between DC voltage and AC voltage in detail. Section 3 outlines the market trends that can be linked to the five market segments. Section 4 illustrates the benefits and drawbacks of the application of DC voltage in combination with power electronics. Section 5 focuses on the current market adoption of DC voltage within the market segments. Section 6 outlines the general difficulties facing market adoption. Finally, Section 7 details conclusions and recommendations for future policy making and innovation.

2 What are DC and AC voltage?

This section explains the practical and physical differences between DC voltage and AC voltage. It also focuses on how changes to electricity generation and use of electricity are driving the development of DC voltage.

2.1 Use of DC and AC voltage

When electricity systems were developed at the end of the nineteenth century, AC voltage (alternating current) emerged the winner of the 'War of the Currents'. The principal reason for this was that voltage was easy to transform and that energy could be transported in this way without significant losses. In addition, AC voltage electric motors were both efficient and inexpensive. Today's electricity system still works with AC voltage. Power plants using non-renewable sources such as gas and coal produce AC voltage and most domestic appliances are designed to connect to the existing AC voltage grid.

Change in the generation of electricity

A transformation is currently taking place in terms of both electricity generation and use. Generation is now more locally focused and small scale, using wind turbines and solar PV. PV panels supply DC voltage (direct current). To use this current on the grid, inverters are used to convert the DC voltage into

AC voltage This inversion results in an energy loss. Wind turbines generate AC voltage because of their 'rotating' generators, but this voltage is still converted into DC voltage[1].

Change in use

Internal DC voltage/power electronics are also used in many devices, including mobile devices containing microchips such as laptops, smartphones and tablets, as well as televisions, USB-C devices, LED lighting, electric vehicles, heat pumps and batteries. These applications have seen increasing use in recent years due to trends in digitalisation, improved energy efficiency and the energy transition. In addition, DC voltage is also used for lengthy electricity cables such as the NorNed cable to Norway, in which case it is known as 'High Voltage Direct Current (HVDC)'[2].

In order to convert the AC voltage from the grid into DC voltage for these applications, a converter must be used for each application, whereby electricity is lost. The increase in the use of DC voltage applications means that more electricity will be lost in these converters in an AC voltage-oriented system.

In addition, AC experiences more energy losses due to the 'skin effect', 'corona effect' and radiation and induction losses. This creates a break-even point at which point HVDC is more cost effective than HVAC. On land, this break-even point lies at around 400 - 700 km, and at sea, at about 25 - 50 km.

1) The rotational speed of the rotor or turbine in the wind turbine is often different to the frequency of the AC voltage grid. In order to match the frequency of the AC voltage to the grid, the voltage is first rectified and then inverted back to AC voltage at the correct frequency.
2) Use of HVDC rather than HVAC is financially attractive over long distances. AC/DC converters are more expensive than AC/AC converters, but AC voltage cables are more expensive when compared to DC voltage cables as distance increases. This is due to the larger amount of conductors required by AC voltage, the construction that needs to be reinforced and on account of the fact that DC requires fewer cables. https://www.electricaltechnology.org/2020/06/difference-between-hvac-hvdc.html

2.2 Developments relating to DC voltage

In view of the growth in DC applications for the generation and use of electricity, AC voltage is increasingly being converted to DC voltage or vice versa. Power electronics are required to rectify and convert or invert voltage. This technology is relatively new. The physical properties of DC voltage make it more difficult to transform voltage levels. This is explained in greater detail in paragraph 2.3. Developments in power electronics also give rise to an 'opportunity' for further development of DC voltage infrastructure at different scales, going beyond 'traditional' DC voltage applications (trams, trains, trolleybuses).

The combination of innovation in power electronics and the growth of DC voltage applications are sharpening the focus on DC voltage and opening up discussion on the logic behind the choice for AC voltage. As power electronics are increasingly required, the question arises as to whether or not DC voltage grids might not be a more logical choice for certain applications. Still, the electricity grid is large in size and incorporates billions of Euros in assets, which will last for many decades to come[3]. A total changeover of the system in the short term is, therefore, almost inconceivable and would not add significant value in each and every situation. Consequently, it is important to look at different market segments and the possibilities offered by DC voltage within each of them. This should be done by first outlining the differences between DC voltage and AC voltage and then by looking specifically at segments in which the benefits of DC voltage could offer the greatest added value.

2.3 Differences between DC and AC voltage

2.3.1 Physical

The difference between DC voltage and AC voltage is that the voltage and current in AC change direction repeatedly, while in DC, they always move in the same direction. The change in direction creates a sine wave when the voltage is plotted against time. This is shown in Figure 1. This means that the voltage of an alternating current alternates between negative and positive, with zero in between. The point at which the voltage is zero is known as the 'zero crossing'. DC voltage does not have a zero crossing as the voltage and current do not change direction. This has major implications for components when it comes to transformation and protection. The core of the new protection system with power electronics is to keep the current as constant as possible and to monitor it continuously. To avoid high/large currents and, in particular, current changes in DC, additional measures need to be taken. Inrush currents must be prevented, short-circuit currents cannot be supplied from sources behind a converter. The use of short-circuit currents as a protection mechanism is, therefore, no longer possible.

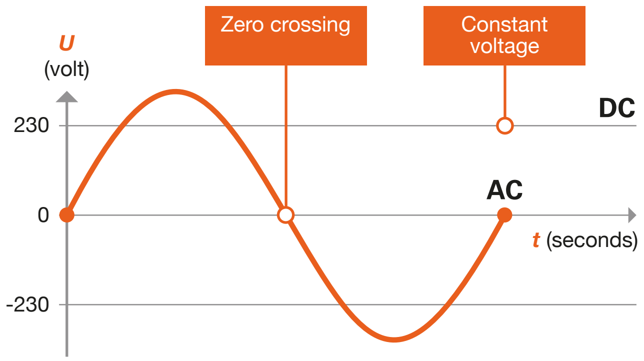

Figure 1 Properties of DC voltage and AC voltage

The rate of change of direction of current and voltage in AC voltage is known as the 'frequency'. The property of frequency is a zero crossing. This applies to both voltage (V) and current (A). In the Netherlands, the frequency is 50 Hz, which means that current and voltage both pass through zero 100 times per second (Figure 1). The frequency is important for the balance in the electricity grid, where demand must always equal supply. If supply exceeds demand, the frequency increases, and vice versa. For AC, it is important that supply and demand in Europe remain in balance; the frequency is, therefore, an indicator of the stability of the electricity grid. In the case of DC, the balance cannot be expressed as a frequency as it does not change direction, which is why voltage is used instead. The balance of DC with voltage is of local importance, within the coupling of a DC voltage grid. In a nutshell, with AC, voltage and frequency are the most important parameters for stability. With new DC, with electronic protection, the voltage level is the most important indicator. If there is excess energy, the voltage rises (in AC, the voltage rises and in extreme cases, the frequency also rises) and when there is excess demand/shortage of supply, the voltage falls (in AC, the voltage falls and in extreme cases, the frequency also falls).

For local applications, voltage changes in a DC voltage grid can be measured with a simple voltmeter. As a result, excesses or shortages within a local grid can be detected more easily in the case of DC voltage. When voltmeters are implemented in devices, they can respond (without or with external control) to the status of the grid based on set bandwidths in voltage. For smart, active control, additional control mechanisms such as in grid codes are required for both DC voltage and AC voltage applications.

A further difference that arises from the sine wave for AC voltage is the maximum power output for the same current. The effective voltage (Vrms) of AC voltage is the maximum voltage divided by √2 (root 2). This does not apply to DC voltage. With an equal maximum voltage, the power with DC voltage is therefore at least 1.41 (√2) times higher than with AC voltage[4]. Additionally, on paper, there is the potential for more capacity with AC voltage (also root 2). In practice, however, both of these effects must be established independently. The ability to rely on a limited short-circuit power can further increase capacity. Figure 1 demonstrates this difference in power in the difference in the (absolute) areas of both lines.

2.3.2 Practical

The zero crossing of AC voltage has benefits for system components. Consequently, voltages can easily be transformed to higher or lower voltages without the need for power electronics. This makes it easier to transport power through high-voltage AC voltage grids without high conversion losses. Moreover, other components such as circuit breakers can also use this zero crossing[5]. When working with DC voltage, these components must be adapted.

Additionally, the lack of zero crossing in DC voltage applications also affects the protection. As the voltage is never zero, a flame arc will not automatically extinguish. Consequently, this form of mechanical and/or electromagnetic switching cannot be used and DC voltage must be protected differently. This can be done with the aid of active protection, where switching is carried out electronically rather than mechanically. In that case, there is a form of code of conduct for the grid between the power source and connected devices, thus allowing for faster and more precise protection. This technology (power electronics) is not specific to DC voltage and can also be used with AC voltage, although it is not (yet) commonplace in the latter.

With the growth in electricity use and the local generation of electricity, there is now an increase in the use of power electronics. An inverter is used for the switch from DC voltage to AC voltage, a rectifier for AC voltage to DC voltage and a converter for AC voltage to AC voltage and DC voltage to DC voltage. Semiconductors and electrolytic capacitors are used to rectify current. These capacitors are sensitive components and require considerable maintenance. Other capacitors can also be used that have a longer service life, but electrolytic types are typically used due to their low cost. As more power electronics are added and as the grid is used more intensively, the maintenance requirement will increase even further. Additionally, each addition of power electronics gives rise to energy loss.

On a wider scale, the growth of power electronics has an adverse effect on the current AC grid— these effects are referred to collectively as 'power quality'. This has an impact on the service life of sensitive equipment. The key difference in the influences of power quality in AC voltage and DC voltage grids is in frequency-dependent components. These do not feature in DC voltage grids. For example, these include the impure sinuses created by the imperfections in power electronics. Non-frequency-dependent components of power quality remain the same—the effect of inrush currents, for example. Frequency monitoring and enforcement also cease to be a feature in DC voltage grids, thus reducing the complexity of problems relating to power quality.

3) This document looks at the situation in the Netherlands. Additionally, there are hundreds of millions of people around the world with no access to electricity. In those areas, there is a blank page and full DC voltage grids may be the future, particularly as this dovetails with a system of decentralised generation involving solar PV and battery systems.

4) At a voltage of 325 V and a current of 16 A, with AC voltage: 325 V/√2 x 16 A = 3.68 kW over the cable, with DC voltage: 325 V x 16 A = 5.2 kW. (325 V/√2 = 230 V; this voltage on the current AC grid is, therefore, the Vrms). The power with DC voltage may be more than 1.41 times higher as the current also changes direction, adding another factor of 1.41. Whether or not this is actually the case in practice remains in dispute.

5) In an AC voltage circuit breaker, magnetism breaks the circuit when the current is too high. Because there is not alternation in DC voltage, and there is no magnetic pole that changes direction, this electromagnetic method of protection does not work.

3 Market trends linked to DC voltage

As outlined in Section 2, AC voltage is used in present-day power grids. Although AC voltage remains the standard to this day, there are a number of market trends that will have an impact on the consideration for AC voltage or DC voltage in the future. These market trends may be new technologies that were not previously available or technologies that, due to a changing society, will become widely adopted in fairly short order. Within this there are a number of trends: digitalisation and portable devices, innovation in power electronics and changes arising from the energy transition.

Changes arising from the energy transition: electrification and renewable generation

An important trend that is influencing the development of DC voltage is the energy transition, a result of which is a high degree of electrification. This electrification manifests in the technologies being used, such as PV panels, heat pumps and electric vehicles. Many of these devices work with DC voltage. Figure 2 illustrates the growth of a number of these technologies.

Here, we can see a fivefold increase in the number of electric vehicles. Additionally, it is anticipated that the proportion of electric vehicles will continue to rise in the future as the Climate Accord aims to achieve 100% sustainability for all new vehicles by 2030, for example. The batteries in electric vehicles are charged with DC voltage. The number of PV panels and heat pumps has also risen considerably— the number of PV panels in the built environment is nearly nine times higher and the number of heat pumps is three times higher when compared to 2014. Generally speaking, this means an increase in the proportion of DC voltage equipment, and more conversion from AC voltage to DC voltage. Moreover, this will also mean that energy previously provided by natural gas and motor fuels will now be returned in the form of electricity. With full electrification, this could triple a household's demand for electricity[6]. This will have an impact on our electricity grids, which have not been designed for this level of change, with the potential for grid congestion as a result.

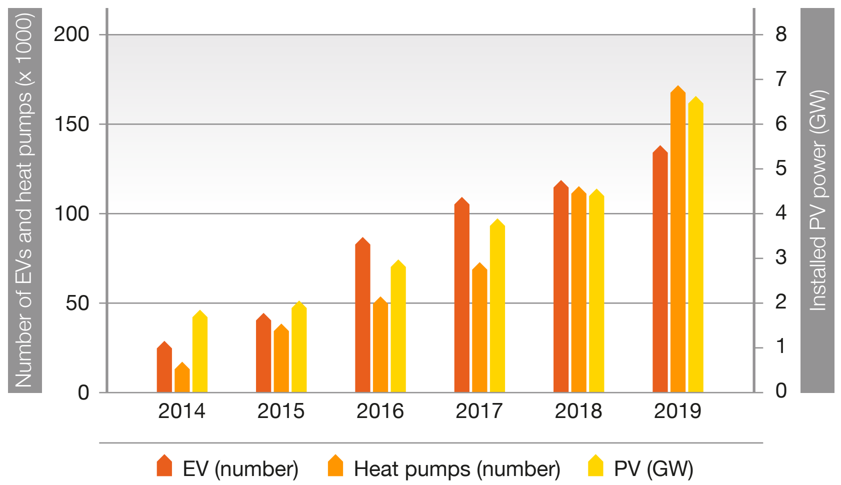

Figure 2 Growth of energy transition technologies (source: CBS, 2020)

6) Berenschot, Systemic issues in the energy transition for the climate tables consultation process (2018)

The energy transition is also having an impact on the way we cook. The extent of electric cooking will increase as a result of a move away from (natural) gas. This, in conjunction with the growing use of heat pumps and electric vehicle charging, will lead to an increase in peak electricity demand during the evening hours.

In terms of lighting, there is also a trend towards more LED lamps. In many cases, incandescent and halogen bulbs are being replaced because of the greater efficiency of LED lamps (more lumens/watts), resulting in energy savings. This trend is expected to continue. Internally, LED lamps operate on DC voltage, so can easily be connected to a DC voltage grid.

In addition to the electrification of consumption, there are also major changes on the generation side. Rather than demand-driven power plants, the system is increasingly focused on intermittent renewable generation, such as solar and wind energy. These forms of generation are integrated into the system on a decentralised basis[7)]. These are also DC technologies (for an explanation of wind energy, see the footnote in paragraph 2.1), where solar energy in particular exerts a high simultaneous load on the electricity grid and is often used in buildings on a decentralised basis. By using DC grids, these energy transition technologies can be more efficiently integrated into the current energy system. To illustrate, a local combination of solar energy, batteries (whether or not in electric vehicles) and, inter alia, heat pumps[8)] could partly help to prevent grid congestion[9)]. The benefits of DC voltage in the integration of these technologies is looked at in more detail in Section 3 and in the white papers.

Digitalisation and the growth of portable equipment

Another important trend is digitalisation. Over recent years, electronic equipment has become increasingly important to society. This trend is expected to continue in the form of 'smart technology', 'smart cities' and the 'Internet of Things (IoT)'. Digitalisation makes extensive use of electronic equipment, including sensors, and therefore correlates strongly with an increase in electricity consumption. Another example of digitalisation is the growth in consumption of portable devices, such as mobile phones, laptops and smart watches. All of these technologies use batteries that are charged via USB-C using DC voltage. and thus influence the choice for DC voltage.

Innovation in power electronics

Additionally, recent years have seen various developments in power electronics, which enable the control, switching and conversion of electrical power. As an example, the improved energy performance of domestic appliances can largely be attributed to the use of these new power electronics. In the future, it may also be possible to protect a grid with the aid of power electronics, something that is currently still done mechanically. A DC voltage grid can only be protected with power electronics—mechanical protection does not work with DC voltage. This does not mean that power electronics can only be used in a DC voltage grid— AC voltage systems and grids can also use power electronics in what are known as 'smart transformers', as well electronic protection.

3.1 System integration (coordinating supply and demand)

Many of the aforementioned trends have an influence on one another, as well as on the electricity grid. Growth in demand for electricity and growth in local generation will, therefore, exert greater pressure on the electricity grid. Challenges in this regard are likely to increase only further as more local generation is integrated into the system. Consequently, the grid will need to be reinforced. An alternative to this is to coordinate supply and demand. This will allow the electricity grid to keep pace with developments and trends that are now being detected. The use of DC voltage may help to prevent the need for grid reinforcement by making better use of existing cables and through smarter design, whereby technologies respond passively to the voltage in the grid.

In the current grid, system integration can be facilitated through 'smart technology' that controls other technology. Within this, devices can be controlled manually or automatically with the aid of a data connection and an external control system. A drawback of this setup is that a physical connection is needed between the converters and that the data connection could open the system up to hackers. An advantage for DC voltage is that no physical connection is needed for the data connection as communication can be carried over the DC voltage cable by means of power-line communication (PLC).

In a DC voltage grid, there is also the possibility of a passive response to the voltage level with the aid of set bandwidths. This would allow the system to offer local balancing options based on local conditions, perhaps without external inputs such as prices/tariffs. This would not achieve the same level of control as 'smart technology', but the passive response to the voltage level could be of interest for certain devices and may help to prevent or minimise the need for grid reinforcement. This applies to appliances that can handle their required power flexibly, often because they can store heat or electricity or because a process, such as heating an oven, is not impaired if it takes a longer. Other examples include boilers, heat pumps and electrical transport. This would allow overloads in a DC voltage grid to be prevented with relative ease without significantly higher costs for installation or management.

3.2 Focus on market segments

In the Netherlands, the entire energy system has already been designed, known as a 'brownfield' situation. This makes it unrealistic to apply DC applications to the grid as a whole (all at once). More likely is that DC voltage will first become established in certain market segments and in certain locations and grow from there on a gradual basis. Accordingly, we have opted to outline the market trends for five specific market segments in this study— five market segments in which it is anticipated that DC voltage can offer added value in the short term. The trends and corresponding market segments are indicated in Figure 3. The figure shows that innovation in power electronics is linked to the application of DC voltage in all market segments. Additionally, all market segments are affected by at least one of the three trends in respect of the energy transition. The market segments that the white papers focus on are:

- Residential and non-residential buildings
- Greenhouse horticulture
- Charging infrastructure
- Public lighting grids
- Local DC voltage grids

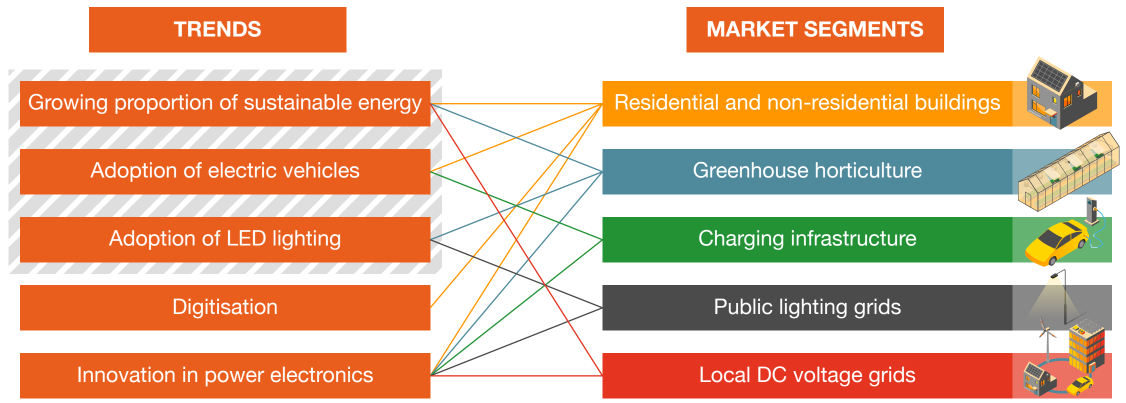

Figure 3 Market trends linked to DC voltage with corresponding market segments

7) Climate Accord as signed in 2019
8) Berenschot, Systemic issues in the energy transition for the climate tables consultation process (2018)
9) Berenschot (2020): Climate-neutral energy scenarios 2050

4 Benefits and drawbacks of DC voltage

The combination of DC voltage and power electronics offers benefits. In this section, we look at the generic benefits and drawbacks of DC voltage. These benefits and drawbacks apply to DC voltage in general. The white papers take a more detailed look at the specific benefits of DC voltage within a market segment. Additionally, we also look at the benefits of power electronics in view of their prominent role within DC voltage.

4.1 Benefits of DC voltage

- **Saving on equipment**
  When multiple DC voltage devices are connected to a DC voltage grid, the number of AC/DC converters decreases, and the number of DC/DC converters increases. This conversion is currently carried out for each device individually. When devices are supplied by a DC voltage grid, individual conversion is no longer necessary. AC/DC converters cost more in terms of equipment (around twice as much) than DC/DC converters. Using DC/DC converters instead of AC/DC converters therefore helps to save on equipment. In addition, copper wire can also be saved because DC voltage allows for a higher capacity on the same wire, as discussed in paragraph 2.3.1. The wire can, therefore, deliver the same power with a smaller diameter.

- **Increased service life**
  As outlined in Section 2, AC/DC converters use electrolytic capacitors to limit/prevent energy loss at the zero crossing. These capacitors age relatively quickly and generate heat. In addition, these electrolytic capacitors cause the surrounding material to age more quickly on account of heat development. As other capacitors can be used in a DC voltage grid (no zero crossing needs to be accommodated), which age less quickly and produce less heat, the service lives of the components in the system or grid increase. With AC voltage, other capacitors can also be used but seldom are for cost reasons.

- **Maintenance**
  By using fewer electrolytic capacitors, the equipment wears less quickly (see Increased service life). As a result, fewer inspections and/or maintenance are required. In addition, grids can be operated in an ring-shaped structure, allowing voltage to be maintained on the part not being maintained while maintenance is carried out on the other side of the grid[10]. In a DC voltage grid, feed-in can come from the other side with no downtime, as the ring is always connected on both sides. In an AC voltage grid, switching must happen before feed-in from the other side. Additionally, maintenance is more predictable as changes in voltage can be more accurately signalled and, therefore, problems identified more quickly. A change in voltage, for example, could indicate corrosion or bad contacts.

- **Energy savings**
  When an electricity source (solar PV) and a consumer (electric vehicle) are connected to the same DC voltage grid, there is no need for DC/AC inversion and AC/DC conversion (compared to current commonplace situations). There are, however, more DC/DC converters. DC/DC converters are more efficient than AC/DC converters, resulting in small energy savings when switching to a DC voltage grid. Experts disagree on the extent of the efficiency gain and whether or not the gain is sufficient enough to be classed as significant. There is some consensus that the gain is a few percentage points at most. In specific applications, the gain may be significant compared to existing converters, where there is often room for improvement.

10) AC grids are also configured as rings, but are operated radially. This means the power is fed in from only one side. During maintenance, power needs to be 'diverted', which means that the voltage needs to be removed from the grid temporarily. This is not the case with DC voltage, and in a ring-shaped grid, the voltage remains in the grid while maintenance is being carried out, with the exception of the section that is being worked on.

- **Passive control based on (local) voltage**
  A DC voltage grid enables individual applications in the grid to be influenced via power demand on the basis of local voltage. Apparatus are set to a certain limit value. When the device detects the limit value, it is set to demand less power, for example, or to shut off completely. As an example, when the voltage drops below a certain threshold value, the heat pump and vehicle charger switch to demanding less power. This way, devices can ensure that the grid does not become overloaded. With AC voltage, it is not possible to reactively control devices on the basis of voltage, as the voltage changes constantly (frequency).

- **Reduced voltage drop**
  When a grid is connected to DC voltage, there are no capacitive leakage currents, which, in AC voltage grids, cause voltage drops. This means that there is reduced voltage drop in a DC voltage grid. This benefit is multiplied as cable length increases. Additionally, a DC voltage grid can be fed from two sides. Generally speaking, this means that the inverter in the transformer station is closer to the user, so there is reduced voltage drop and less electricity is lost overall. With DC voltage, fewer inverters are therefore needed over longer distances.

- **Increased capacity**
  As the voltage in a DC voltage grid remains constant, the effective voltage is higher than that in an AC voltage grid. This voltage is $\sqrt{2}$ times higher than in an AC voltage grid. Additionally, the current is also—in theory—$\sqrt{2}$ higher, although there is uncertainty as to whether this is actually true in practice. Voltage and current correlate directly with the capacity of a cable. This means that at least $\sqrt{2}$ times as much energy can be transported along the same cable when compared to an AC voltage grid. Investigations must demonstrate whether this is 2x $\sqrt{2}$, i.e. $\sqrt{2}$ for both current and voltage.

- **Increased power quality in a DC voltage grid**
  An increasing number of power electronics are being incorporated into our grids. Problems with 'power quality' occur with both AC voltage and DC voltage, such as with inrush currents. The difference is that there is no frequency in a DC voltage grid, also for the power quality problems that depend on frequency. Accordingly, a DC voltage grid has fewer variables than an AC voltage grid on the basis of which power quality must be guaranteed (see also Section 2).

4.2 Drawbacks of DC voltage

- **Lag in adoption of DC voltage**
  The electricity system is designed for AC voltage, which has created something of a 'lock-in'. This means that devices are compatible with AC voltage, that all current devices operate on an AC grid and that legislation (such as grid codes) are designed accordingly. Consequently, current devices in residential and non-residential buildings are not suitable for a DC voltage grid. In turn, large amounts of devices will need to be redesigned to be compatible with DC voltage grids. The regime created by large-scale use of AC voltage also means that competing with it is a challenge, as AC voltage components are already produced on a large scale and have already achieved strong cost reductions. Additionally, DC voltage manufacturers now produce both DC voltage and AC voltage components, so there is competition between the components within the same company.

- **Flame arcs**
  When a plug is removed from an AC voltage socket, there is a very brief flame arc. This arc is quickly extinguished as the voltage falls to zero several times each second. Mechanical switching works on the principle of creating a physical distance between two wires, in which case there is a flame arc that is extinguished very quickly on account of the voltage being zero 100 times per second. With DC voltage, this is not the case, so the arc remains. Consequently, mechanical switching should be avoided in a DC voltage grid. This makes it necessary to switch with the aid of power electronics.

- **Solid state components**
  As DC voltage does not change direction and has no zero crossing, other types of components are required to protect the system—these are called 'solid state components'. With these components, it is not possible—without further indication—to tell whether they are switched on or off. This is a disadvantage, as with AC voltage, there must be a visible physical switch. Consequently, there is a lack of acceptance of these components amongst professionals.

- **Lack of electricians with knowledge of DC voltage**
  A lack of knowledge among electricians plays a role in current DC voltage applications. Electricians are trained to work safely with AC voltage and are unfamiliar with DC voltage systems. This could give rise to unsafe situations. A number of concrete projects have shown that it is difficult to find electricians with knowledge of DC voltage—the interviews have also indicated this.

4.3 Power electronics

Power electronics are used to switch, control and convert electrical power with the aid of electronic components. There have been a number of developments in power electronics in recent years, which has meant that they are increasingly being used in power grids. The benefits of power electronics over a grid without power electronics are discussed below.

- **Protection using power electronics**
  Protection with the aid of power electronics enables switching in a DC voltage grid. Additionally, power electronics also enable more accurate protection and rapid detection of leaks and overflows.
  - Switching
    As the flame arc is not broken with DC voltage, mechanical switching cannot be used. Power electronics do make electronic switching possible, however. Power electronics can detect whether or not there is (mechanical) switching and immediately remove the current, thus preventing the flame arc.
  - More rapid protection
    When compared to mechanical protection, electronic protection can be much faster. Where there is electronic protection by means of power electronics, the system switches off immediately. In an AC voltage grid, by contrast, switch-off only occurs when the voltage passes through the zero crossing. This makes electronic protection faster than mechanical protection, as mechanical protection only switches off at the speed of the frequency. Electronic protection is not dependent on frequency and is, therefore, able to switch off more quickly.
  - Rapid detection of grid faults
    Power electronics can quickly detect imperfections in the grid, including leakage currents and overflows. If these currents are detected, a system can be switched off quickly. This makes electronic protection safer than the current method of (mechanical) protection on account of the speed.

- **Conversion of DC to DC**
  A DC/DC converter is an example of power electronics. These power electronics enable the voltage in a DC voltage grid to be increased or decreased, thus allowing DC voltage grids to be constructed.

- **Controllability by means of PLC**
  Power electronics enable smart power-line communication (PLC) over power cables, thus making it easier to control applications. This is more robust with DC voltage than AC voltage applications, as AC voltage can interfere with PLC signals.

5 Lessons from the Roadmap

A DC Voltage Roadmap was put together in 2018 to outline the added value for DC voltage in seven market segments. In addition, a timeline was also prepared for seven market segments, indicating when DC voltage would be market ready in that specific market segment. The Roadmap also makes a number of general recommendations needed to further progress in DC voltage. The recommendations in the Roadmap are:

- Provide targeted support for the most promising application areas for DC voltage micro-grids: the public lighting grid and greenhouse horticulture
- Stimulate knowledge development, pilots and demonstration projects aimed at eliminating uncertainties regarding the (social) business case for DC voltage micro-grids
- Support the hedging of financial project risks
- Create flexibility in legislation for experimentation
- Develop professional training courses for power electronics focused on DC voltage applications or their application in DC voltage micro-grids.

What has happened since then?
In terms of support for promising application areas, a great deal has happened within public lighting grids. A number of new projects have emerged, including some without subsidy. Additionally, DC voltage in public lighting has been able to compete with AC voltage in some projects. By contrast, very little has happened in greenhouse horticulture in recent years and there have been virtually no developments.

Additionally, existing developments/projects in the other market segments have continued. Still, there remain many uncertainties in respect of the business case for DC voltage in several market segments, as interviews and the validation session (see the Annex for a list of participants) have demonstrated. The financial risks are not yet hedged in every market segment and DC voltage still often loses out to AC voltage in many cases. Since the 2018 DC Voltage Roadmap, there has also been no change in legislative flexibility. There are still no training courses in power electronics focused on DC voltage applications, although expertise and knowledge are being shared in other ways (webinars/conferences/WhatsApp groups).

A number of lessons were learned from the DC Voltage Roadmap. The lessons in the Roadmap chiefly focus on supporting promising application areas, stimulating pilots, hedging financial risks, creating flexibility in legislation and developing professional training courses in power electronics.

5.1 Anticipated timelines/market adoption

The DC Voltage Roadmap looks at seven market segments and outlines market adoption and future development of these market segments. This update is based on five market segments, with residential and non-residential buildings merged into one and the data centre market segment not included. Progress in market adoption was gauged by means of interviews with experts. These showed that the greenhouse horticulture market segment has been delayed when compared to the 2018 Roadmap. The forecast market adoption for the other market segments continues as outlined in the Roadmap, as shown in Figure 4. This shows that charging infrastructure using DC voltage and public lighting using DC voltage are further into their development than the other market segments. These market segments will be the first to be market ready, and thus show the greatest opportunity for DC voltage in the short term. By contrast, greenhouse horticulture would appear to be developing more slowly than initially anticipated, particularly the adoption of LED lighting, which is slower than expected and which is seen as one of the key trends for the application of DC voltage within greenhouse horticulture.

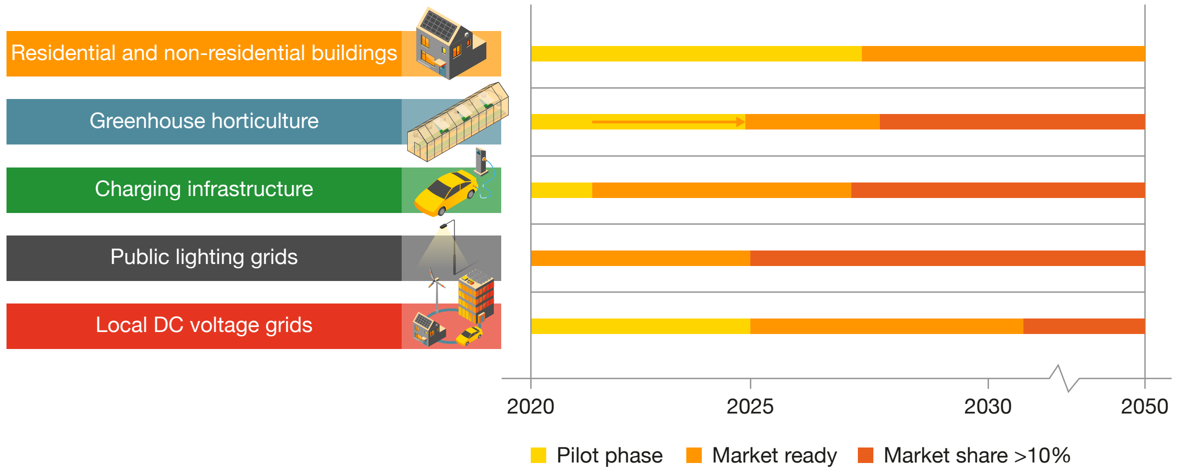

Figure 4 Anticipated timelines for market adoption for greenhouse horticulture, charging infrastructure, local DC voltage grids, public lighting and residential and non-residential buildings

The five white papers look more closely at the current state of affairs and market adoption of DC voltage application in the individual market segments.

6 Difficulties faced by DC voltage

As outlined in Section 4, there are several benefits of using DC voltage in conjunction with power electronics. In many market segments, however, DC voltage is not yet market ready. This section identifies difficulties and bottlenecks in the general development of DC voltage. Specific difficulties faced by individual market segments are looked at in the separate white papers. The general difficulties identified heavily influence one another, as shown in Figure 5.

- **Standardisation of DC voltage components**
  As DC voltage is not yet widely in use, NEN 1010 has not been adapted to accommodate it. NEN 1010 contains the minimum safety requirements that a LV grid must satisfy. Consequently, there are no standards that guarantee safety. As a result, there is a lack of knowledge amongst electricians, for example, and the market is somewhat reluctant when it comes to choosing DC voltage applications.

  In addition, there is a lack of CE certification and product standards, which means that it is not always possible to sell devices. This creates a cycle in which manufacturers fail to focus on DC voltage devices because there is no certification, so no device gets placed on the market and, as a result, no further research is carried out into devices.

  Another difficulty for standardisation is the lack of legally recognised measuring equipment for DC voltage. DC kWh meters do exist, but charging for electricity on the basis of these meters is not yet permitted. This has an impact on the application of DC voltage within charging stations, residential buildings and local grids.

- **Knowledge of DC voltage opportunities and usage**
  A lack of knowledge poses a difficulty to the development of DC voltage in two ways— awareness and expertise. It has been suggested that market parties are not always aware of the existence of DC voltage or of DC voltage components. If users are not aware of the benefits or existence of DC voltage, it is impossible to properly weigh up the benefits of AC voltage over DC voltage and vice versa. In that case, users will always opt for the more familiar AC voltage.

  Furthermore, there is little knowledge of the design, installation, use and maintenance of DC voltage grids, systems and applications. There are no standards in place for system design, which means that few grid designers are familiar with the design of DC voltage grids and systems. The problem also applies to electricians, who are generally ill-informed when it comes to safely maintaining DC voltage systems. This can be attributed to a lack of practical training for electricians in DC voltage.

- **Availability of DC voltage components**
  There is currently no certification or standardisation for DC voltage components and DC voltage devices. This means that manufacturers do not yet have the courage to develop DC voltage products on a large scale. Project developers, therefore, have only a limited choice of DC voltage components. In addition, components are not always available or have long lead times, which means that project designs need to be modified or suffer delays.

  In addition to the fact that companies do not produce DC voltage products on a large scale, there are very few companies active in the DC voltage component market. This makes it impossible for project developers to choose between different producers and allows suppliers to set prices for products without taking competition into account. This is one reason why the price of DC voltage components remains high and supply limited.

- **Safety and perception of safety**
  As outlined above, a DC voltage grid requires a different form of protection. Safety components are available to achieve this, but there is no standardisation and there is no certification for these components. Accordingly, the perception is that DC voltage is less safe. This preconception is based on a lack of knowledge about the operation of power electronics in DC voltage technology. This perception of safety has been identified as a difficulty impeding the development of DC voltage in general.

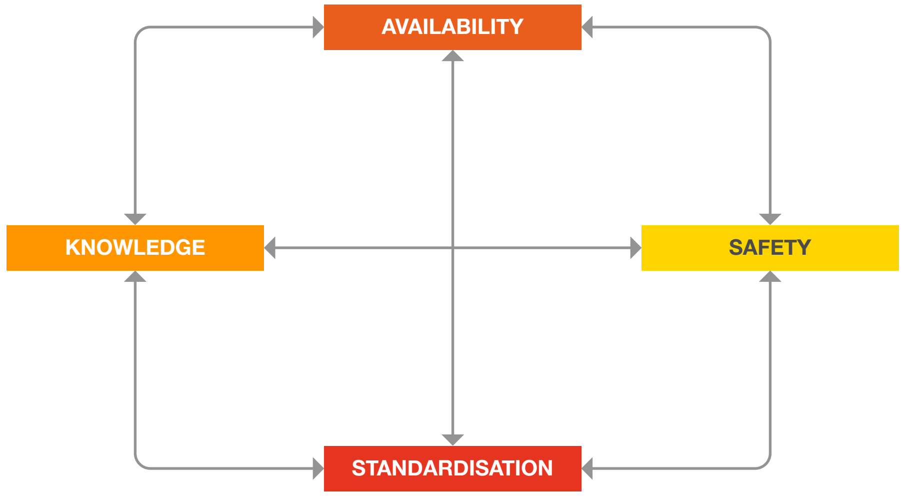

Figure 5 Dependence of the difficulties for the development of DC voltage

7 Conclusions/ recommendations

In this section, we look at the overarching conclusions from the interviews and the validation session. We offer a number of recommendations relating to the development of DC voltage. Additionally, we discuss how DC voltage dovetails with the government's Mission-Driven Innovation Programmes (MMIPs). We conclude the section with a definition of the roles of the Netherlands Enterprise Agency, TKI Urban Energy and Stichting Gelijkspanning Nederland in the development of DC voltage.

7.1 Innovation policy (MMIPs)

As part of the Climate Accord, the government has drawn up an Integral Knowledge and Innovation Agenda (IKIA) which outlines the innovation challenge that needs to be overcome to achieve the set climate targets. The IKIA includes thirteen Multi-Year Mission-Driven Innovation Programmes (MMIPs), which describe this innovation challenge for the five missions.

DC voltage touches upon two of the MMIPs.

- **MMIP 5. Electrification of the energy system in the built environment.**
  This programme aims to contribute to an efficient, affordable, smart and integrated electricity system, to which DC voltage can contribute in several ways. As demonstrated by the 'Residential and non-residential buildings' white paper, DC voltage can contribute to the optimal use of electricity grids due to the increased power that can be transported along cables and the possibilities offered by droop control. This also applies to local DC voltage grids, where potential future grid congestion may be avoided through better utilisation of existing infrastructure and bundling of renewable generation within a DC voltage grid. The application of DC voltage in public lighting grids can also contribute to the programme by making use of parallel utilisation. In addition, DC voltage in the charging infrastructure can contribute by taking a smart approach to energy flows by means of V2G.

- **MMIP 9. Innovative propulsion and use of sustainable energy carriers for mobility.**
  This programme aims to contribute to a sustainable mobility system in the Netherlands and includes the development of efficient and effective charging infrastructure. As stated in the 'Charging infrastructure' white paper, the combination of DC voltage charging and V2G is promising. In addition, linking several DC voltage chargers (e.g. in a charging hub) can allow charging speeds to be controlled more easily than with AC voltage.
  This is not only interesting for high power fast charging, but relevant for slow charging as well.
  The public lighting and residential and non-residential buildings market segments touch upon this programme because of the linkage options with electric charging.

7.2 Recommendations for policy and innovation

The recommendations for the development of DC voltage were leveraged from interviews and the validation session. The recommendations in this section are general recommendations for the entire DC voltage sector. Specific recommendations for each market segment are presented in the respective white papers.

- **Stimulate standardisation**
  The development of DC voltage requires standards for the use of DC voltage as current standardisation is very limited when it comes to DC voltage. Many different areas of the industry cite the lack of standardisation as a difficulty. The (accelerated) standardisation of DC voltage would remove a major obstacle for both the production of components and the installation, design and application of DC voltage grids. It could also help to give potential users confidence in the safe application of DC voltage.

- **Legislation**
  Another point that is important for the development of DC voltage is the lack of legislation (such as grid codes and measurement codes). This issue is twofold, with both a lack of a legally recognised DC kWh meters and anchoring of standards in law. A DC kWh meter is available, but it has not yet been legally recognised, which means that it is not possible to use it to charge for electricity in a DC grid. It may seem a trivial point, but is essential for the use of DC voltage grids—the billing of energy flows is the foundation on which the system is maintained. This is a barrier to further development in several market segments. Additionally, the standards outlined in the previous point must be anchored in law (by means of grid codes and measurement codes) so that users can have confidence that DC voltage is being used both professionally and safely.

- **Demonstrations and pilots**
  In general, there have been too few demonstrations and pilots in the field of DC voltage. Consequently, there is thus far no clear quantification of the benefits over the current system. Additionally, there is a lack of a 'proof of concept' at different scale levels for wider application of DC voltage. In certain segments, significant claims have been made about the benefits of DC voltage, but this has not yet been proven in demonstrations. As such, there is now a discussion between those who do and those who do not believe in DC voltage. We recommended, therefore, focusing on demonstration projects and pilots, where the benefit of DC voltage can be proven and substantiated.

- **Monitoring and evaluation**
  Changes in the field of DC voltage are progressing apace and sometimes in unknown market segments. It is recommended that developments within DC voltage be monitored on a structural basis (e.g. annually). It is possible to create a link to SGNL, which maintains a list of all DC voltage projects.

7.3 Role of TKI Urban Energy and the Netherlands Enterprise Agency

The validation session indicated that expectations of the role of TKI Urban Energy and the Netherlands Enterprise Agency are close to the current role. Experts indicate that they see a role in the stimulation of specific demonstrations and pilots and the provision of subsidies. It is noted that the new setup of mission-driven innovation policy[11)] provides sufficient leads for subsidising innovation projects, but that it is important to continue to provide sufficient resources for separate projects focused on the necessary (further) development of technical components as well.

Both bodies are recognised for their role in sharing outcomes and lessons learned from DC voltage projects. In addition, it is also suggested that TKI Urban Energy and the Netherlands Enterprise Agency can encourage large parties such as grid operators to participate in large-scale projects. By focusing on the interaction between major parties, the link between demonstrations and standardisation can be strengthened. For grid operators in particular, there are many benefits for the application of DC voltage still being identified. This is notwithstanding the fact that virtually no activities carried out by grid operators have been identified[12)] in respect of research into or application of DC voltage.

7.4 Role of Stichting Gelijkspanning Nederland

A clear role is foreseen for Stichting Gelijkspanning Nederland as a link and point of reference in bringing parties together and actively sharing knowledge. The role as knowledge sharer is already concretised in, for example, the sharing of 'best practices', but also in raising awareness of DC voltage. Stichting Gelijkspanning Nederland is also seen as a party that can clarify the role of DC voltage for governments and grid operators. Consequently, Stichting Gelijkspanning Nederland is also seen as a lobby party. The development of different business cases focused on the future could also play an important role here.

11) Since 2019, subsidies have been awarded along the lines of the Multi-Year Mission-Driven Innovation Programmes (MMIPs). Within this, there is a strong focus on the development of integrated solutions. DC voltage touches upon the following two MMIPs in particular.
  - MMIP 5: Electrification of the energy system in the built environment. This programme aims to contribute to an efficient, affordable, smart and integrated electricity system,
  - MMIP 9: Innovative propulsion and use of sustainable energy carriers for mobility. This programme aims to contribute to a sustainable mobility system in the Netherlands and includes the development of efficient and effective charging infrastructure.

12) There was not enough scope within this investigation to interview all grid operators on this topic. It is recommended that further discussions be held with grid operators on this topic.

Annex

Interviewees

To prepare this update, we amassed knowledge of the market segments and the general application of DC voltage through, inter alia, interviews. The table below lists the interviewees and associated organisations.

Name	Organisation
Wilfred Akerboom	Citytec
Pavol Bauer	Delft University of Technology
Martijn Bongaerts	Alliander
Richard van Bueren	Gavita International
Johan Driesen	KU Leuven
Menno Kardolus	PRE
Mark Kousman	Eaton
Henry Lootens	Stichting Gelijkspanning Nederland
Laurens Mackay	DC Opportunities
Jan van Os	ATAG Nederland
Wim van Raalte	Delft University of Technology
Goffe Schat	NEN
Korneel Wijnands	Eindhoven University of Technology

Attendees at validation session

A digital validation session was held on 10 November 2020, during which people from the industry were able to respond to the insights in the draft white papers. The results of this session were then incorporated into the white papers. The table below lists the attendees and associated organisations.

Name	Organisation
Wilfred Akerboom	CityTec
Ron Bakker	HTM
Wessel Bakker	DNV GL
Pavol Bauer	Delft University of Technology
Paul Borghouts	Nexans
Sven de Breucker	Dynniq
Giel van den Broeck	DCINERGY
Marcel Eijgelaar	DNV GL
Erik Elich	Municipality of The Hague
Ronald Fransen	Stichting Gelijkspanning Nederland
Menno Kardolus	PRE
Nicole Kerkhof	Netherlands Enterprise Agency
Mark Kousman	Eaton
Henry Lootens	Stichting Gelijkspanning Nederland
Laurens Mackay	DC Opportunities
Sander Mertens	HHS
Wim van Raalte	Delft University of Technology
Maarten van Riet	Alliander
Rob Schaecke	Amsterdam University of Applied Sciences
Goffe Schat	NEN
Marco van Steekelenburg	Province of South Holland
Harry Stokman	Direct Current
Maarten de Vries	TKI Urban Energy
Korneel Wijnands	Eindhoven University of Technology
Pepijn van Willigenburg	Stichting Gelijkspanning Nederland