Low Voltage DC Grids

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Most electrical devices operate on direct current (DC) internally, but are supplied by alternating current (AC). A power supply with DC allows omitting the rectifier electronics, which makes the devices simpler, more reliable and generates less power losses.

This publication aims to show solutions of DC operated professional buildings like offices or supermarkets and homes. A realized office test bed including DC light emitting diode (LED) illumination and photovoltaic (PV) support is presented as well as a detailed concept for a DC operated home. Based on these reference cases, the specifications of the components for those applications are derived and the saving potentials in material and power losses for different use cases are illustrated.

1 Introduction

Most electrical devices operate on direct current (DC) internally, but are supplied by alternating current (AC). A power supply with DC allows omitting the rectifier electronics, which makes the devices simpler, more reliable and generates less power losses.

This is attractive for lighting applications, especially in installations, where a high number of lamps are connected to a power rail like in open space offices or supermarkets (see Figure 1). Each lamp contains an AC to DC conversion circuit, which can be omitted with a DC supply rail. This becomes especially attractive, if the system is combined with a local photovoltaic generator, as shown in [1].

Figure 1 Typical ceiling of an open space office (*left*) and in a supermarket (*right*).

In a home environment the applications are more versatile. But especially in the entertainment and home office area DC supply can save a lot of circuitry when using low voltage grids.

Figure 2 Illustration of the reference DC home (adopted from [2]).

Furthermore, also in a home photovoltaic (PV) energy supply (see illustration of a reference home in Figure 2, from [2]) and battery storage will be relevant in the near future and both are DC devices by nature.

A publication by Wu et al. [3] gives an overview of the technology, which can be used for this purpose. Here, the necessary specifications for the components are derived.

This publication gives an overview of the opportunities of using a DC grid in professional and home buildings. They are demonstrated on a realized installation of an office building DC lamp system with PV support at Philips Research, Eindhoven and on an exemplary planning of a DC installation in a home with PV and battery storage, performed by master students at the Cologne University of Applied Science.

2 Effort for AC to DC conversion

Figure 3 shows the block diagram of a typical lamp driver operated on AC with the parts necessary for AC to DC conversion. Similar components are necessary for all AC power supplies.

The rectifier is the essential element and is typically a bridge rectifier consisting of four diodes. The electrolytic capacitor (elcap) levels out the pulsating rectified sinusoidal voltage. Recently IEC SC77A WG1 agreed to a new review of the standard IEC 61000-3-2, which means that in the near future lamp drivers with more than 5 W will require a power factor correction (PFC) circuit. A PFC ensures that the current drawn from the grid is sinusoidal. The PFC may consist of an inductor, but this is usually too bulky. Especially for higher power levels a switch mode converter, typically a step up converter (boost converter), is used. However, this requires a filter to avoid higher frequency content generated by the switched mode PFC polluting the grid.

2.1 Space and components saving

Figure 4 shows a photograph of a Philips Xitanium lamp driver for a 39 W light emitting diode (LED) lamp as used in the reference setup (see later chapter 5). In the figure, all parts, which are necessary for AC to DC conversion, are marked. As can be seen, approximately 40% of the printed circuit board (PCB) is occupied by these components. Especially the PFC and the filter circuit require a lot of space. The storage elcap is also significant, but the bridge rectifier itself is a comparable small component.

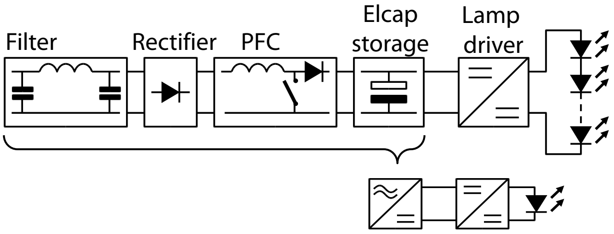

Figure 3 Typical AC lamp driver.

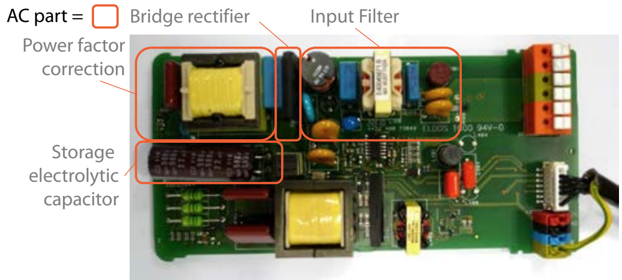

Figure 4 Philips Xitanium 39 W LED driver.

As now discussed, these components might also be necessary for DC operation. An overview of this is shown in Table 1.

The bridge rectifier may be necessary to allow an arbitrary connection of the DC supply leads. However, this problem may also be solved by a suitable mechanical coding of the plug to avoid a wrong connection.

The elcap may be needed to suppress voltage dips of the DC supply. However, it should be acceptable for lamps to pass the dips to the lamp and allow a short flicker. Then, an elcap is not necessary.

Component	AC supply	DC wide voltage range and reverse polarity protection	DC narrow voltage range, mechanical rev. polarity protection
Filter	Required because of PFC	Required because of DC-DC	Can be omitted with linear driver
Rectifier	Required	Required for reverse polarity	Omitted
Power factor correction (PFC) / DC-DC converter	Required for P > 25W	Required to match wide voltage range	Not necessary
Elcap storage	Required to avoid flickering	Required because of dips	Can be omitted, if dips are accepted

Table 1 Overview of required components for AC to DC conversion.

If the DC supply voltage has a large variation, it may be necessary to convert it to a constant level of an intermediate voltage. This requires a DC to DC converter, similar to an active PFC. However, if the DC voltage range has a narrow specification, such a DC to DC converter can be omitted.

The filter is necessary to suppress high frequency contents of switched mode converters. It becomes necessary, if an active PFC is used. If the lamp driver itself uses switched mode conversion, it remains necessary. However, with a linear lamp driver, even the filter may be omitted.

Concluding, the components needed for AC to DC conversion can be omitted if the DC power plug is mechanically coded, if dips can be accepted, if the voltage is specified in a narrow range and, optional, if a linear lamp driver is used.

2.2 Linear LED driver

The advantage of a lighting DC supply becomes most obvious with LED lamps. A most simple “driver” for a LED is simply a resistor. If the supply voltage is very well defined, this would be the most simple, reliable and durable “lamp driver”. However, if the voltage is less stable, the brightness of the LED would vary remarkably, because a small voltage variation already leads to large change of the output power.

A nearly as simple solution is a linear current driver. Such a linear current source can easily be built with one J-FET and one resistor. Such a circuit may exhibit a good efficiency. The efficiency of such a circuit is calculated assuming a constant forward voltage U_d of the LED and neglecting a residual voltage drop at the FET. The results are presented in Figure 5. As long as the DC supply voltage U_s is larger than the forward voltage U_d, the LED power (blue) is the nominal value. If the supply voltage increases above U_d, the voltage across the FET rises linear. The power loss in the FET (orange) increases proportional to it. From the LED power and the losses the efficiency (yellow) is calculated.

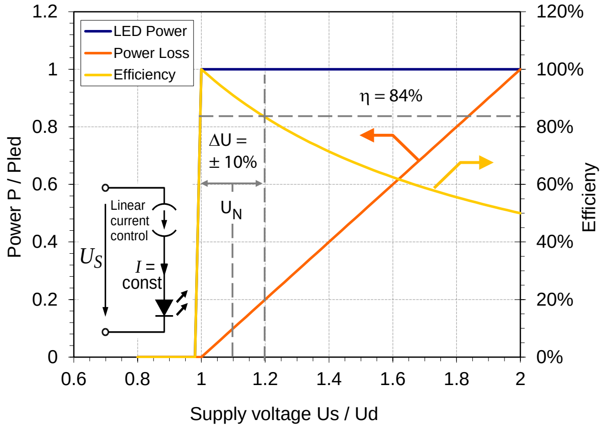

Figure 5 Power losses and efficiency of a linear LED driver.

If the voltage variation is within ±10% around the nominal voltage U_N (like in the public AC grid as well), the efficiency can still be above 84%. This simple and reliable circuit can thus achieve an efficiency, which is similar to small switched mode converters, as long as the voltage range is narrow enough.

2.3 Loss savings

The components needed for AC to DC conversion also generate losses. Typically, the smaller the device is, the lower is the efficiency. Own measurements showed losses in the order of 5% of the output power for lamp drivers. This arrangement is shown in Figure 6a. These losses can be saved, if the device is operated on DC. However, if the DC grid is supplied from the AC grid, a central rectifier is needed in addition. However, this central rectifier can be more efficient due to its larger size. Its losses are estimated to about 2% of its output power, as illustrated in Figure 6b. In addition, cable losses can be reduced, if a DC voltage of 380 V is used, as shown in Figure 8 (chapter 3). In total, losses of about 5% of the output power could be avoided using a 380 V DC grid.

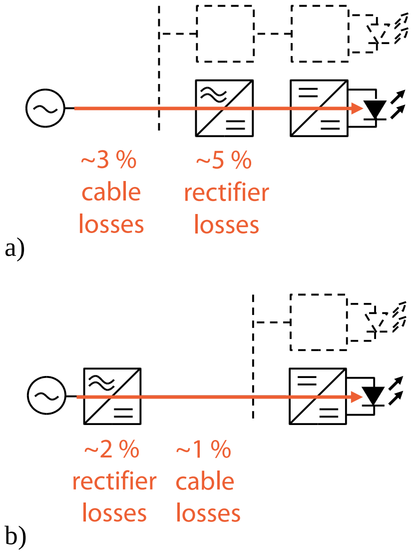

Figure 6 Loss breakdown for supply from AC grid:
a) AC grid. b) DC grid.

Even larger loss savings can be achieved in a different use case as illustrated in Figure 7. It shows a system, which is optimized for self-consumption of photovoltaic (PV) energy. The PV energy harvested during the day is stored in a battery storage and used in the evening.

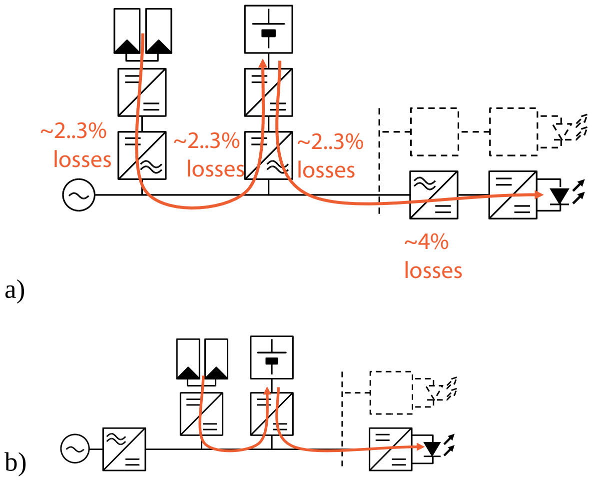

Figure 7 Loss breakdown for micro-grid supply from photovoltaic with battery storage:
a) AC grid. b) DC grid.

If all components are connected to the AC grid, losses in the AC to DC (and vice versa) converters end up to 10% to 13% of the output power (see Figure 7a). In a DC system, these losses can be completely avoided (see Figure 7b).

3 Voltage selection

The supply voltage of the DC grid also has an influence on the losses. Low voltages like 24 V or 48 V have as advantages that they are save to touch and commercially available devices exist. However, to transmit the same power, much higher current I is necessary compared to 230 V AC. A high DC voltage like 380 V is compatible to many 230 V AC devices, which operate on a similar intermediate DC voltage internally.

The power loss P_{loss} in the cable is proportional to the square of the current I: $P_{loss} \sim I^2$. Figure 8 shows the cable losses which appear at different supply voltages, scaled to the losses at 230 V AC. To achieve the same losses at higher currents, the cable cross sectional area A must be also scaled proportional to the current: $A \sim I^2$. Therefore, the same Figure 8 shows the amount of copper, which is necessary to achieve the same losses as with the 230 V AC supply.

It is clearly seen that the low voltages of 24 V and 48 V either generate extremely higher losses or require significant more copper. It also shows that a 380 V DC supply generates only about 1/3 of the losses compared to 230 V AC. It should be noted that insulation properties of 230 V AC cables are also suitable for 380 V DC operation, because they need to withstand the peak voltage.

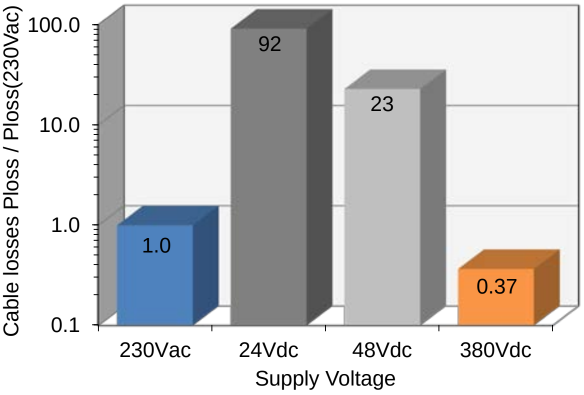

Figure 8 Relative cable losses (equivalent to copper effort) scaled to 230Vac supply. *Remark*: 380 Vdc requires similar insulation as 230 Vac.

4 Standardization on 380 V DC

The voltage level of 380 V DC is not only attractive for lighting applications, but also for other applications like the power supply in data centres. Most advantage will be available, if the DC supply system is standardized. Several organizations work on the standardization. Table 2 gives an overview of the organisations and their current work.

Organization	*Topic*
International Electrotechnical Commission (IEC)	Many standards covering low voltage DC grid systems already
	SMB SG4 working group “LVDC distribution systems up to 1500V DC”: Managing new standardization projects at IEC technical committees (TC)
	National standardization working groups. Germany: TBINK-LVDC working group at DKE/VDE
European Telecommunication Standardisation Institute (ETSI)	European Standard: EN 300 132-3-1 V2.1.1 (2012-02)
	Value: Definition of DC appliance inrush current limits and measurement setup
EMerge Alliance	Standardization working group on 380 V DC power grids for datacenters
	Standardization working group on 380 V DC for campus and microgrids

Table 2 Overview of organisations working on standardisation of low voltage DC grids.

5 DC lighting demonstration setup

To demonstrate the functionality and to experience the problems related to it, a DC lighting demonstration is setup in an office building at Philips Research in Eindhoven, The Netherlands. Figure 9 shows a schematic overview of the system.

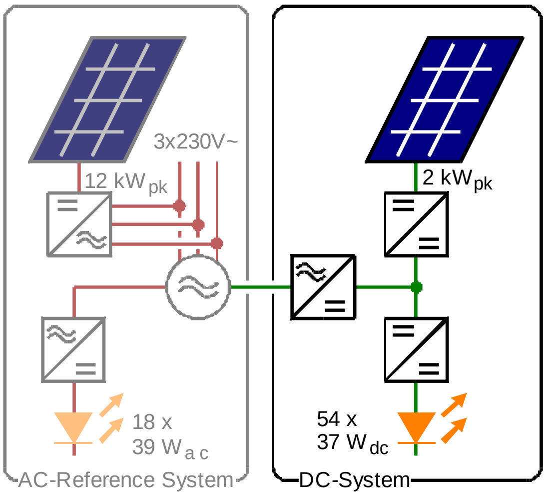

Figure 9 Demo DC-Grid with Solar Support.

Figure 10 Photos of the demo DC grid installation: *Left*: Photovoltaic panels. *Right*: DC driven LED lamps.

The DC part consists of a rectifier, a 2 kW$_{pk}$ photovoltaic (PV) generator and 54 LED lamps with 37 W each. Figure 10 shows photographs of the PV panels and of the some of the lamps. The lamps illuminate the floor and are switched on during the whole working hours at daytime. In the best case, the PV generator is able to supply all the DC lamps. No feed in of PV power into the AC grid is provided. The lamps are Philips Xitanium lamps, with drivers modified for DC operation.

For reference, AC system is also in operation. Here, the PV power is directly fed into the mains grid. Furthermore, 18 comparable AC operated Xitanium LED lamps are monitored. The system was installed early in 2013. To present reasonable results, a whole season should have been passed. Therefore it is too early to present a comparison of the AC and the DC system.

6 DC supply in a home

6.1 Devices in the home

In a home, the requirements for the power supply are much more versatile than in an office building. To get an overview of the needs, the power supply of a whole living house was planned. As reference, a house plan of a company offering energy efficient buildings was used [2] (see Figure 12). The infrastructure includes a 150 m^2 photovoltaic generator on the roof. To improve the photovoltaic self-consumption a battery storage is provided in the cellar. It is assumed that the family owns an electric vehicle. Therefore, a charging station is available in the cellar garage. Cooking is done with electric energy. As in a real home lamps of different technologies are used: Halogen lamps and LED lamps in living rooms, where a high light quality is desired, fluorescent lamps in working areas, where a high light level is needed. Various entertainment and office devices are assumed, distributed over the rooms. In the kitchen, typical household appliances are considered. Publication [4] lists usual devices in a household including their power requirements as well as typical duration and daytime of operation. The devices used for the planning of the DC home are based on this list.

6.2 Considered infrastructure

Analyzing the devices, a large variety turns out. For a few, large power consummators it makes no sense to operate them on DC. Examples are the kitchen oven, heating system or some kitchen devices, where the power is mainly used for a motor. Here, no rectifying is necessary when operated on AC, and thus operation on DC neither saves energy nor reduces complexity. Contrary, it would add a lot of unnecessary AC to DC conversion effort to the infrastructure. Therefore, it is decided to keep an AC supply for those devices.

On the other hand, a lot of small energy consumers operate on safe low DC voltages below 50 V. Here, a large number of AC to DC converters could be saved, which would reduce the complexity of many mass products.

However, different voltages are used because of several reasons. Offering only one safe low DC voltage would severely reduce the design freedom of those devices and would often lead to a DC to DC converter in the devices. Therefore, we propose a DC supply with different voltages. A multi-contact socket can provide these different voltages simultaneously. Here, a solution with four different voltages related to a common ground is proposed. Table 3 lists the voltage levels, which result from the most commonly used voltages. Additional voltages can be used, if the voltage difference between two contacts is used. This is possible, if the device is isolated from others. This solution requires a cable with 5 wires, where for example a standard 5-wire 2.5 mm² NYM cable could be used. It should be mentioned that special care must be taken to design an appropriate multi-contact DC socket to make sure that sparking during unplugging doesn't cause any harm [5].

Halogen and LED lamps are also operated with safe low voltage and can be supplied by the same system. Fluorescent lamps would require a further, higher DC voltage to directly operate them on DC. But their small number does not justify a separate DC power supply. Therefore, they are operated on 230 V AC in the reference home.

6.3 Infrastructure requirements

With these considerations the infrastructure of the house was planned as shown in Figure 12. In this part, the DC infrastructure will be investigated more in detail. Sockets and lamps are connected by cables to central rectifiers located in the room dedicated for the house technique in the cellar. In the ground floor, 4 cables are provided, in the first floor also 4 cables and in the cellar only 2 cables. The length of the cables varies from 5 m to 26 m. Figure 11 shows the statistical distribution of the lengths. Only one cable is longer than 25 m. Therefore, a maximum standard length of 20 m is proposed. For longer distances special measures (e.g. thicker cables) must be provided.

The current in a cable can be limited by two effects: Either the voltage drop along the line becomes too high or the losses in the cable are too high. Calculations showed that at 20 m length the voltage drop is the limiting factor. Here, a maximum voltage drop of 10% of the nominal voltage (similar to the requirements in the public grid) is assumed, which also relates to the results in chapter 2.2. The maximum current and the related transmitted power is calculated for different cable cross section areas, which are commonly used. The results are shown in Table 4. With a cross section of 2.5 mm², already 200 W can be specified for the 24 V wire and 50 W for the 12 V wire, which is sufficient for most devices, which would make use of this kind of supply. The 9 V line can provide only 28 W. Here, only low power devices should be connected. These power limits are taken as a specification for each cable. If all installed cables are able to deliver the maximum power at the same time, the rectifier must be able to deliver the sum of the power. Table 5 gives an overview of the necessary power requirements in the reference home. They are derived from Table 4. Taken the specification of the 2.5 mm² wires, the rectifier must be able to deliver up to 4 kW.

Probably, this power can be reduced, because not all devices are in operation simultaneously. To find a suitable simultaneity factor, further investigations will be done.

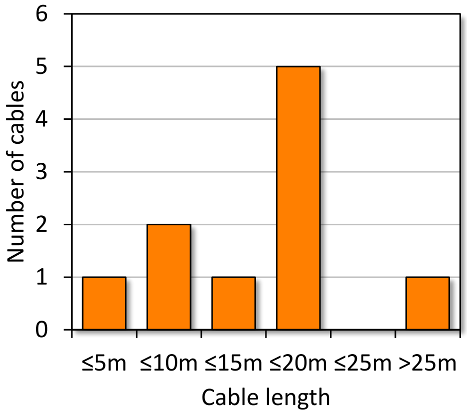

Figure 11 Cable length of the Safe Low Voltage DC distribution.

Wire	1	2	3	4	5
Voltage	9V	12V	19V	24V	0V

Table 3 Safe low voltages used in the DC-supply.

Cross section / mm²	1.5	2.5	4	1.5	2.5	4
Supply voltage / V	Max. Current / A			Max. Cable Power / W		
9	1.9	3.2	5.0	17	28	45
12	2.5	4.2	6.7	30	50	81
19	4.0	6.7	10.6	76	126	202
24	5.0	8.4	13.4	121	202	323

Table 4 Maximum currents and transmitted power on a cable to allow a 10% voltage drop at 20 m length.

Max. Rectifier Power / W									
Cross section / mm²	1.5	2.5	4	1.5	2.5	4	1.5	2.5	4
Supply voltage / V	Ground Floor 4 cables			First Floor 4 cables			Cellar 2 cables		
9	68	113	181	68	113	181	34	57	91
12	121	202	323	121	202	323	60	101	161
19	303	505	809	303	505	809	152	253	404
24	484	806	1290	484	806	1290	242	403	645
All	*976*	*1627*	*2603*	*976*	*1627*	*2603*	*488*	*813*	*1301*

Table 5 Power requirements, if all cables are fully used.

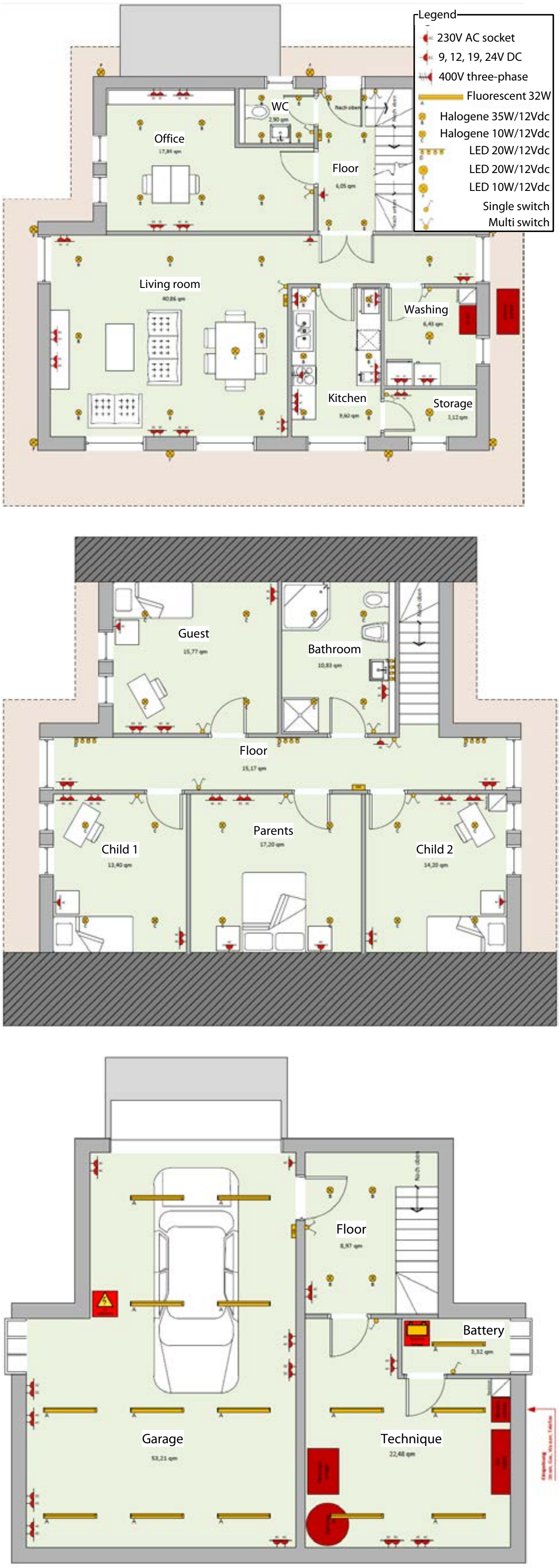

Figure 12 Floor plan of the DC home (based on [2]): *Top*: Ground floor. *Middle*: Top floor. *Bottom*: Cellar.

7 Conlusion

Operating lamps and other devices with a residential DC grid offers two major benefits:

Overall power losses can be reduced. However, for a supply of the residential DC grid from a public AC grid, this effect is partly compensated by losses in the central rectifier. But energy savings become visible especially with the integration of additional local power sources.

As a further benefit, complexity can be reduced in the powered devices by shifting it into the infrastructure. This can make the devices more durable and reliable. Especially for mass products like lamp drivers and consumer devices, which are manufactured and used in a huge number, this will reduce the overall cost. From a system point of view, it is advantageous to make those devices, which are needed in a large number, as simple and cheap as possible and to allow a few central devices being more complex. This cost advantage should be considered as the main benefit of the DC system.

The specification of a DC system should take these benefits into account: To reduce losses in the distribution system, the voltage should be as high as possible. For lamps, an operating voltage like 380 V DC is proposed. To allow the reduction of complexity, especially the definition of a narrow voltage tolerance is required.

8 References

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