Second step to full DC-potential: DC grid efficiency for Home Owners Associations

Conference Paper · March 2015
DOI: 10.1109/DUE.2015.7102968

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Second step to full DC-potential: DC Grid Efficiency for Home Owners Associations

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Abstract— The Energy Agreement for Sustainable Growth (2013, Social and Economic Council) is a long term policy perspective, to bind a sustainable energy supply to sustainable economic growth in the Netherlands. In this agreement, two major targets are directly related to energy. Firstly, an annual saving in final energy consumption of 1,5% is to be achieved, resulting in a saving of 100 PetaJoule by 2020. Secondly, sustainable generation needs to grow from 4,4% (2013) to 16% (2020) of all generated energy.

The Dutch initiated an educational programme 'DC; Road to its full potential' and conducted international research studies into the feasibility of DC-Grids for residential and commercial areas. Results from these earlier studies indicated a potential saving up to 7.5 % when implementing a 350 V DC Grid in a single household, compared to the present-day 230 V AC household grid.

This paper sets out to present a new comparison. The DC-Grid-model is expanded to the street in two different setups. The study compares households with a DC-DC converter per household to households with a centralized DC-DC converter. Several scenarios indicate a centralized setup is to be preferred over decentralized DC-DC converters, especially when centralized renewable energy sources are used. Parameters used for setting up the simulations are evaluated to better value the outcome of these experiments.

***Index Terms*—dc micro grids, home owners associations, energy efficiency, simulations, smart grids**

1. INTRODUCTION TO DUTCH ENERGY POLICIES

September 2013 might very well have been be the beginning of a bright, new and sustainable future. On the sixth of September 2013, the Dutch Energy Agreement was signed by local, regional and national governments, employers organisations, unions and more[1]. This Agreement heralds our country´s ambitions towards a more sustainable future. Numerous NGO´s and government representatives contributed to this document. The strategy sounds simple and convincing: The Netherlands, as a well-performing innovative economy, will aim (part of) their attempts for economic growth on the field of sustainable energy to create innovations[2].

These innovations should lead to three diverse goals: Firstly, an annual saving in final energy consumption of 1.5% is to be achieved, resulting in a saving of 100 PJ by 2020. Secondly, sustainable generation needs to grow from 4.4% (2013) to 16% (2020) of all generated energy. Thirdly, in achieving the first two ambitions, 15.000 new jobs should be created.

One of their focal points is the group of home owners and the way they consume and produce electricity, either individually or collectively, in various participations and cooperatives. In the Netherlands, 625,000 households own their apartments in Home Owners Associations (HOA) that is 8% of all Dutch households [3]. There are presently 121,300 HOA's, ranging in size from two owners to several dozens of owners.

In new legislation, the Ministry of Economic Affairs proposes an exemption to the Energy-bill (1998) to form up local energy networks [4]. Up until now, independent energy and electricity grids are not allowed. From the first of January 2015, local independent energy networks, started by cooperatives or HOA's, are allowed for demonstrator purposes: These demonstrator-grids are test-subjects to enhance involvement of energy users, to enhance more efficient use of electricity infrastructure, or to enhance implementation of sustainable generation for local use. If successful, these new Energy Service Companies and their presumably Smart Grids will be allowed to keep fulfilling their role, to supply sustainable energy in a reliable, affordable and innovative manner.

For future budget cuts new plans are already in the making. The same Ministry of Economic Affairs is proposing legislation that might endanger the present-day attractiveness of photovoltaic installations. Nowadays, both households and small industries are allowed to feed their redundant energy back into the net, to use the electricity grid as storage. Their electricity meter 'ticks' backwards. In the yearly or monthly energy bill, in- and outgoing electricity is balanced. This principle is called ´Saldering´ in the Netherlands. This implies, that the energy that is being delivered or sold to the net, has the same price as the energy that you take up from the net and that taxes for the electricity supply are cancelled out by delivering energy

This work was supported by Regieorgaan SIA under the RAAK-MKB Grant 2012-20-50M.

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back to the grid. And there is one of the problems, from the point of view of the Government.

Consumers in the Netherlands pay energy taxes according to their energy usage. If consumers generate as much electricity as they use, consumers have a zero-usage and they therefore pay no energy-taxes for the electricity that they used from the grid. In reality, the electrical infrastructure is used twice, for both incoming and outgoing streams. Grid service operators are, with present-day technology, unable to distinguish these streams from each other and are therefore unable to bill accordingly. Smart Grids with smart metering, will be able to do just that. These meters enable energy producers and operators to introduce variable rates. Locally generated electricity will yield perhaps € 0.10 per kWh, instead of the € 0.23 per kWh consumers pay nowadays.

So on one hand, Dutch government policies stimulate development of sustainable energy-related innovations, whilst on the other hand, the same Dutch government is changing its ‘rules’ for trading in sustainable energy by small and independent power producers. The real challenge for success is then to combine the consequences of these proposed changes: small and partly independently fed distribution grids for HOA’s in which home owners mutually agree to use their privately generated energy as efficiently as possible.

2. Energy Efficiency in DC-Grids

For valid reasons during the War of Currents, the choice was made to use Alternating Current (AC) as method for distributing electrical energy. Distribution with Direct Current (DC) was not feasible. Power Electronics, since the invention of the transistor (1947) are offering DC a comeback. For transmission over long distances and subsea connections, High Voltage DC is nowadays the only choice. AC is not an option any more.

Low Voltage DC-Grids are yet in the youth of their existence. Research and pilot projects demonstrate advantages of DC: Better energy-efficiency, savings in raw materials, inherent communication and controllability. In addition to that, several sustainable sources such as fuel cells and PV-cells generate DC and consumer electronics work internally on DC. The most important downsides are the necessary transition from AC to DC, the lack of matching standards, the absence of demonstrators at system level and a lack of common knowledge.

To aid to the development of knowledge and application(s) of Direct Current, The Hague University of Applied Science started the ‘DC – Road to its full potential’ programme. This programme is an educational and research programme initiated by The Hague University of Applied Sciences (THU). The programme started in February 2013 and the first part will end in July 2015. The programme is considered ambitious with its four objectives:

1. To gather, capture and create new knowledge on DC-systems, especially in the built environment.
2. To educate both THU students and THU staff in international and relevant projects.
3. To help our partners, especially SME’s, in overcoming knowledge-related obstacles in innovation processes and introducing them to potential partners.
4. To further the cause of sustainable electrical generation by stimulating innovative behaviour of students, staff and partners.

Earlier results of this programme show 1) an expected increase in energy efficiency in industrial and domestic applications of two to four percent, depending on the application [5][6] 2) a significant reduction of usage of raw materials, mainly copper and iron [7]. Projects of partners demonstrated many unexpected side effects: reduction in initial investment, lower installation and maintenance costs, and offering a longer lifespan based on the replaced components [5][8]. In some cases these side-effects are more beneficial than the actual energy-efficiency gain itself, from the point of view of operational costs.

For this paper, we specifically look into the expected energy-efficiency of 350 V DC households compared to 230 AC households [9]. Research has demonstrated:

i. A potential gain of 1.35 % for the 350 VDC in-house installation over present-day 230 VAC household grid.
ii. A potential gain of 4.06% for the 350 VDC in-house distribution grid over the 230 VAC household grid, when both grids are equipped with complex loads and sources as heat pumps, electric vehicles and PV-panels.
iii. A potential loss of 1.15% for the same 350 VDC in-house distribution grid compared to the 230 VAC household, when the DC household used its own bidirectional AC-DC converter
iv. In a fourth comparison, researchers added smartness to the DC-Grid, with adjusted load-profiles to match PV-generated electricity. In this smart grid, with for Europe conventional appliances and PV-panels, the energy savings added up to 7.53% compared to the PV-equipped, not-smart 230 VAC household grid.

The basis for the research is fig 1 below. It shows a small network with an AC load model and a DC load model (A). The DC load is connected to the AC grid by a AC/DC converter (B) with given efficiency.

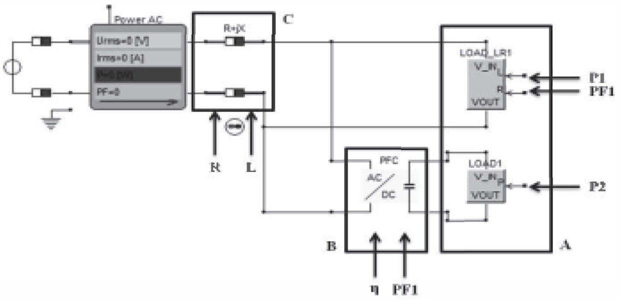

Figure 1: Simulation network[10] on Caspoc software with AC and DC loads (A), AC/DC converter (B) and a cable model (C).

These results suggest that adding 'complexity' to a DC-household-grid enables it to outperform conventional 230 VAC grids in houses. Complexity can be explained as 1) to introduce energy demanding loads as heat pumps, air conditioning, electric vehicles etc., 2) to connect a DC-household to a DC-distribution grid and/or DC-distributed generation, and 3) to add smartness to the grid, to balance energy production and consumption.

To contribute to existing results for DC-Grids, new research was conducted, to model, simulate and analyse several DC-households in what is called a DC Home Owners Grid, with one connection point to the main grid. This grid is compared to a DC-Grid for several individually connected households, with a grid-connection per household.

In the next chapters, we will explain in further detail, the setup of the new model, the simulations that were made, the method of calculating the potential savings and discuss the savings themselves. Lastly, we will evaluate these results with existing and upcoming Dutch energy policies.

3. HOA DC Grid Model – parameters and workings

An important assumption in previous work was the absence of an in-house DC-DC converter. It is however safe to assume that for distribution efficiency, higher voltage levels will be used in larger building blocks, high-rise and Home Owners Associations (HOA). The main focus of this study is to evaluate two different grid lay-outs to connect a five apartment HOA to a 1400 V DC Grid. That voltage level offers benefits for larger power demand, as is shown previously [7]. Such voltage- and power levels make such a grid comparable to a 3-phase AC supply system of roughly 700 V AC. The study uses two research questions:

- Does a centralized and dynamically parallel operated DC-DC conversion offer efficiency benefits compared to a decentralized lay-out?
- Does a centralized PV-system offer benefits compared to a similarly dimensioned, decentralized P-power supply?

To answer these questions, two system models were designed. The first set of models features systems with either a DC/DC converter per household or apartment or a centralized converter. Fig 2 explains the model of a system with DC-DC converters per household (model 1.1). The arrows above and below the left-most DC-DC converter indicate the voltage levels. Above the converter is the main grid of 1400 V DC. Below this converter, the household installation works on 350 V DC.

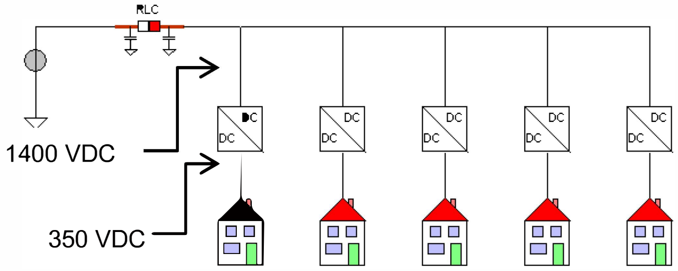

Fig 2: model 1.1 – individual DC-DC conversion

The second model in the first set (model 1.2) in fig 3 represents the system with one centralized DC-DC converter. This converter actually consists of several smaller blocks, activated with rising power demand in the households, thus adding little intelligence to it. The arrows again indicate the voltage levels. On the left or Grid-side of the converter, the voltage level is 14000 VDC, on the right or household side, the voltage level is 350 V DC. All the five apartments are connected to the same 350 V DC bus.

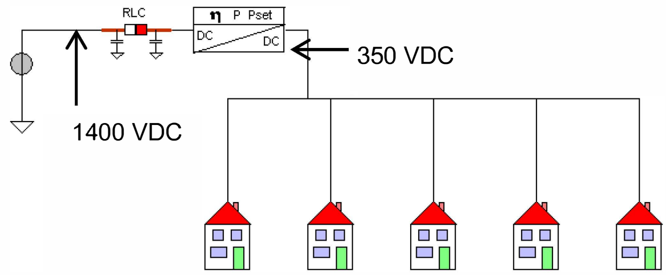

Figure 3: model 1.2 – centralized DC-DC conversion

In more detail, such a centralized DC-DC converter could be a Double Active Bridge (DAB) as displayed in fig 4 on the next page. This can be considered as a DC-DC 'transformer'. The converter is bidirectional and can be placed in series for higher voltage levels, as well in parallel for increasing the load. This parallel operation is what is employed here in fig 4. The secondary part of the converter can be placed parallel with another DAB, doubling the output load capability. By simply disabling the gate-signals, a DAB can be turned off. As soon as the output power demands are rising, the next DAB can become operational, positively contributing to the load demand and thereby sharing the total amount of load power of the number of operational parallel converters.

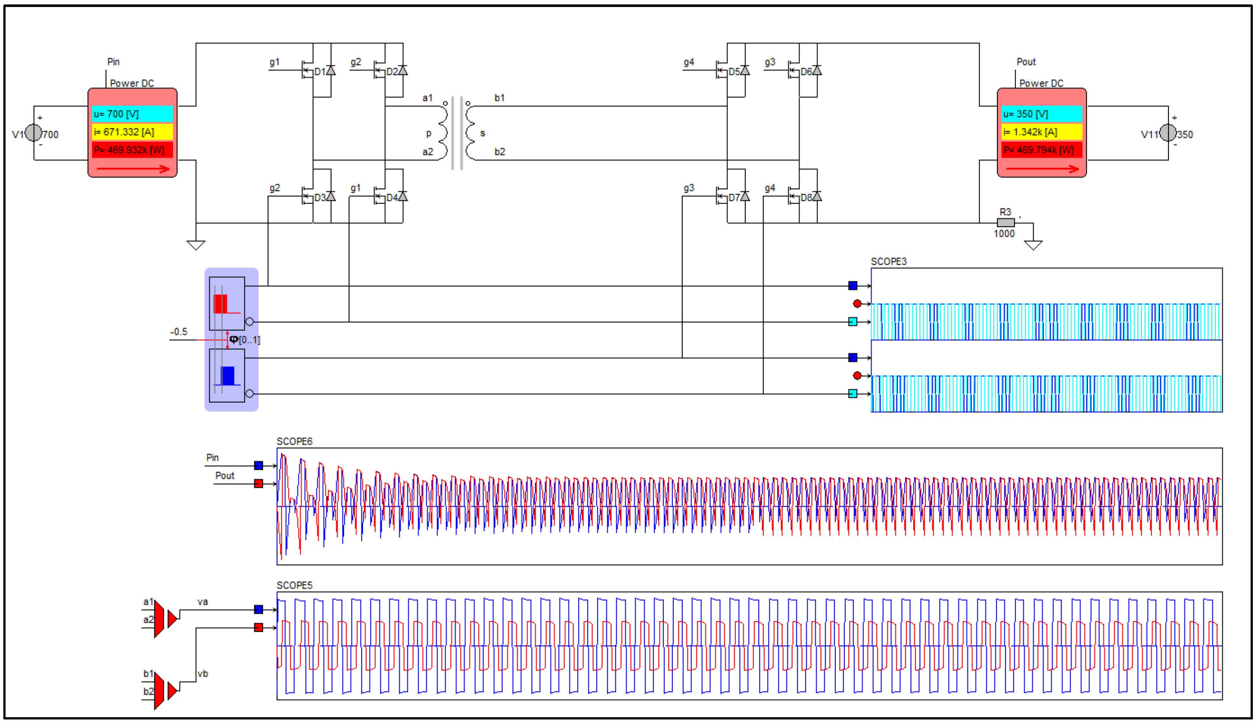

Figure 4: model of a Double Active Bridge (DAB) Converter

The second set of system models is based upon the first set, with the addition of distributed generation: In the model where each household has its own converter, two of these households have a small, private, PV-installation of 3.4 kW peak per household. Fig 5 shows the system model where solar energy is fed into the grid by two of these households. The individual converters can be combined with meters, to measure and possibly invoice especially outgoing flow of electricity.

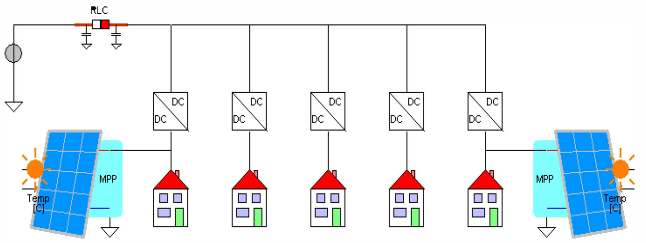

Figure 5: model 2.1 – individual DC-DC conversion and individual PV-installation

And in the model with a centralized DC-DC conversion, there is now a 6.8 kW peak PV-installation, supplying energy to the 350 V DC bus system, for all the households to use (model 2.2). The exact measuring and, if necessary, billing of the separate participants in for example a Home Owners Association can still take place. Each household will be equipped with a meter, to measure ingoing electricity. In both models 2.1 (fig 5) and 2.2 (fig 6) the PV-installations are modeled with a Maximum Power Point tracker per panel and a converter feeding into the DC grid.

This study is not meant to evaluate the actual setup of converter-types, be it a Buck-converter or DAB converter. Therefore the simulation-model uses one curve to represent multiple technological solutions.

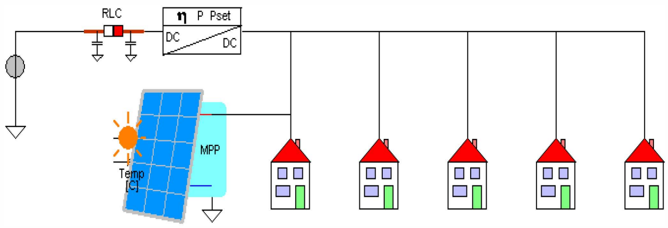

Figure 6: Model 2.2 – HOA with centralized DC-DC converter and PV-installation

The system models will also not contain EV-charging stations. These charging stations are, in the Netherland at least, primarily connected to the utility and not to the household grid. Therefor a centralized or decentralized charging station will not influence the performance of the household or HOA DC-DC converters; they do not handle the power. A third difference between these lay-outs and the Leuven lay-out is that none of the HOA-DC-models are supplied with Smart-Grid Solutions. There will be no balancing of supply and demand.

4. HOA DC GRID – SIMULATIONS

By dynamically paralleling converters, the efficiency is improved for lower and higher energy demands. Fig 7 shows a typical efficiency curve for a DC-DC converter.

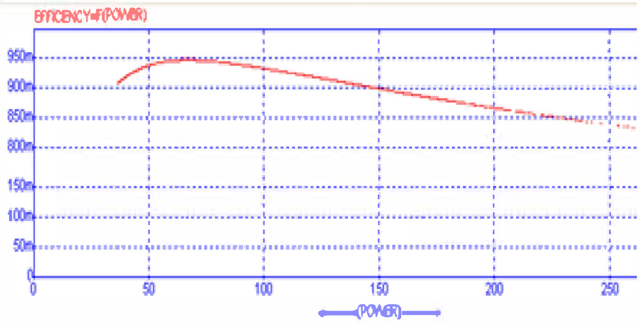

Fig 7: Efficiency as function of load

It is assumed that the highest efficiency is obtained if the converter is operating at its nominal load, which is mostly less than 50% of the maximum load it can deliver. At light load, the efficiency is low due to power consumption in the control and non-load dependent losses in the converter. For higher loads, the efficiency decreases due to increased heating of the semiconductors, leading to rising conduction and switching losses.

A typical household could consume roughly between 50 and 350 Watt continuously, leading to a consumption of 3,350kWh per year in the Netherlands. During the night the consumption can be as low, or even lower than 50 Watt, while during the morning and evening consumption could rise to over several kilowatts.

For the design of the converter, the maximum load is considered the design criteria. However optimum efficiency is not achievable for the whole power range, but only for nominal load. A converter that can be scaled dynamically during operation could literally move its nominal operating point during operation. In this way the optimum operating point could be chosen such as to optimize the overall efficiency of the converter. Fig 8 shows this optimized efficiency as a function of load.

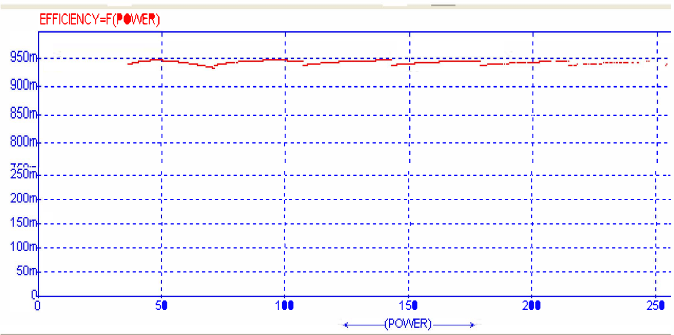

Fig 8: Improved efficiency as function of load with a dynamically scaling converter

The different system models from paragraph three will be subjected to one generalized scenario for energy consumption. This scenario results in a yearly usage of 3,350 kWh per year. That is the present yearly electricity use in the Netherlands. Nowadays most households in the Netherland (83%) use natural gas for cooking and heating, so the figure of 3,350 kWh is little affected by those households that already use electricity for heating and cooking.

To study the impact and advantages of a shared converter, simulation is used. There are a number of requirements this simulation has to fulfil, which led to the usage of the simulation program Caspoc [10], specialized in power electronics, electrical drives and renewable energy. Among the specifications we need specialised models for DC grids, as well as data to check the models against. Fast simulation is a prerequisite, as we are interested to run the model for a data set of one year.

For this simulation study we will use load profiles and solar data for a single year. We run the simulation from the first of January until the last day in December to get better insight into seasonal influences and the day and night difference. Also the load profile includes differences between weekends and working days as well as during public holidays. The data is based on statistical user load profiles in a west-European town/suburb. The solar data applied in this simulation is measured data from a weather station in Nuremberg in southern part of Germany. The converter under test has an assumed efficiency profile resembling a typical converter efficiency. Low efficiency below nominal operation and a reducing efficiency with increase load above nominal operation. Any other load profile, solar data and efficiency curve can be used in the simulation.

The specialized components from the DC library in the program Caspoc allow a typical set up of a DC grid with various users. Both consumers and solar power generation are connected to the DC grid in the simulation, where the DC grid is modelled by a constant voltage source, in series with a typical line impedance. Each user is connected to this grid via a single line. The return line is the common earth line, not explicitly drawn in the schematic, but existing in the simulation model. The DC-DC converters are modelled as a single component, with regulated fixed output voltage and variable input voltage. This allows variations of the DC voltage in the DC grid, without disturbing the output voltage of the converters. Each household is modelled as a single house and uses the exact same load profile.

The solar data set contains sunlight irradiations for a single year built up of hourly samples. The simulation time t is therefore multiplied with 3600 before indexing the lookup table with the solar data. The simulation is run for one year and if there is a surplus of energy during the summer, this surplus is fed back into the grid.

5. Results

When running the simulation for the first set of models, without the PV-installations, results show that using a dynamically scalable converter can lead to an overall efficiency improvement from 92.5% for a non-scaling converter to up to 96.6% for a scalable converter, as shown in fig 4. These percentages are based upon the continuous load profile: at any given time, the load profile is coupled to an efficiency of the converter; (very) low loads correspond for example with low efficiencies. All these instantaneous efficiencies are added up and over the given period of time (a year in this simulation) result in a mean value. The simulation programme calculates this efficiency.

Does this justify the extra investment to make the converter scalable as such a converter would be more costly? That is very difficult to answer straightaway. The running of the simulation with the second set of models (2.1 and 2.2) will help in answering. That is because the effect of individually used DC-DC converters is being multiplied, when adding distributed generation. In fig 5, solar energy from for example household 1(the left-most household) can be used by household 2. That means the electricity first has to be converted to 1400 V DC and then back to 350 V DC again. That means that there are two DC-DC converters in the path, thus reducing the efficiency with 2 times the instantaneous efficiency, for example 0.95. The efficiency of both conversions is then 0.9025. In model 2.2 (fig 6) in contrary, solar energy is fed into the DC bus without a conversion step. It can also be taken up from the same DC-bus without any conversion, leaving only ohmic resistance. It goes without saying that the MPP and converter of the PV-installations do have an effect on the system-efficiency. Because both models 2.1 and 2.2 use the same MPP and converter, the energy that is injected into both 350 V DC systems is identical.

To show the impact of the placing of the converter on the energy-efficiency of the second set of systems, two simulation tests were conducted, one test with each model (model 2.1 and model 2.2). Fig 9 shows the test case where each household has its own DC-DC converter and the solar energy is generated by household number 1 and number 5. Fig 10 shows that excess energy is delivered to the main grid during summer days. That can be seen in the 'negative' curves inside the box drawn around the negative values in figure 10.

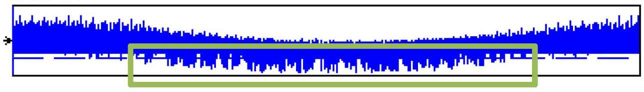

Figure 10: Model 2.1 - yearly load curve

The total area of this fig represents the net energy usage of the five households. The integral is automatically calculated in Caspoc. The overall consumption from the grid

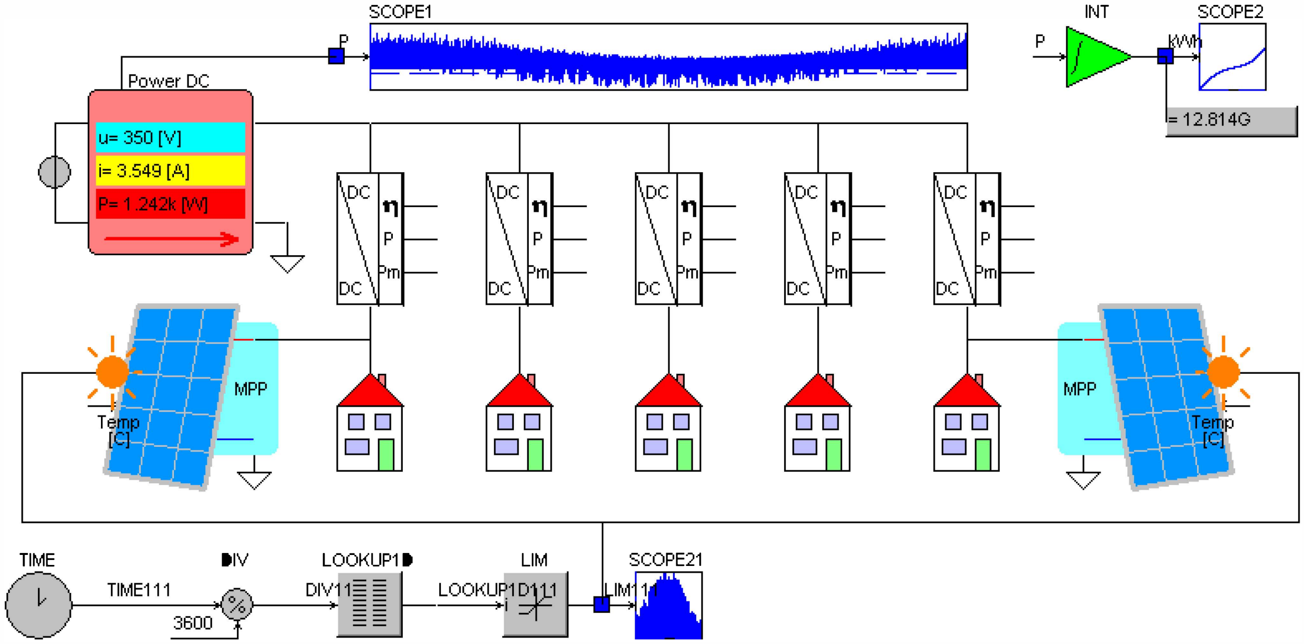

Figure 9: Simulation results of system model 2.1

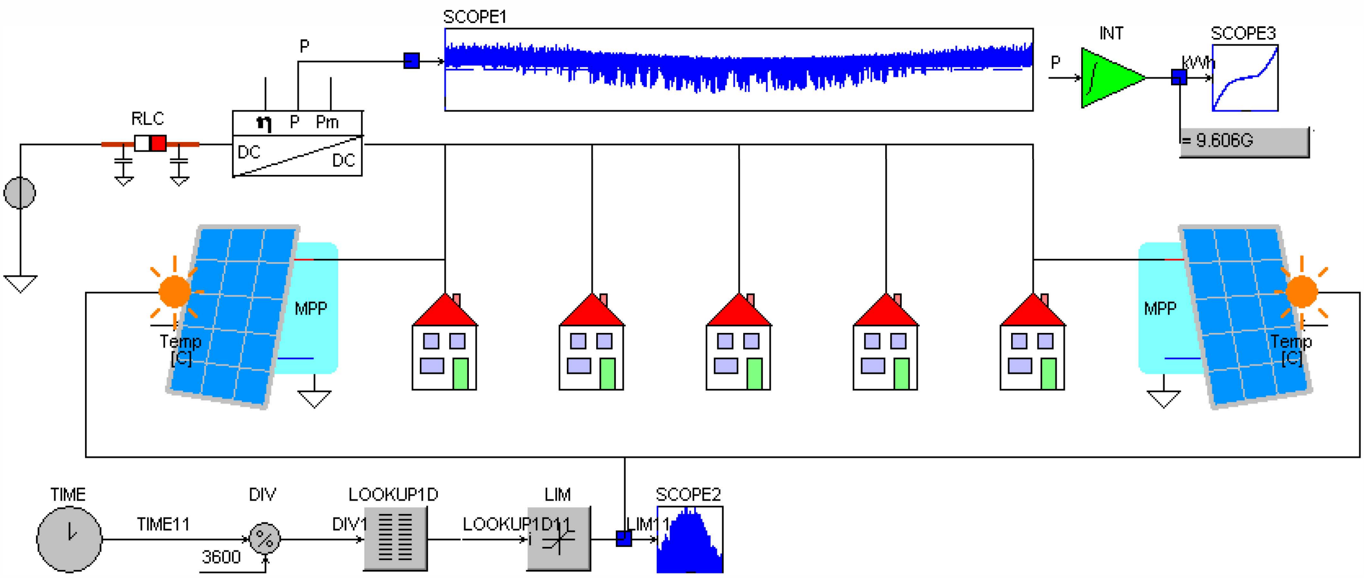

Figure 11: Simulation results of system model 2.2

view and result of this first simulation can be seen in fig 9 on the next page. Within fig 9 the five households and their individual DC-DC converters are displayed. The voltage level after the DC-DC converter is given, and the average current and thus power that flows through the converter on a yearly basis.

This is then compared to the scenario with a centralized PV-system, connected to the 350 V DC bus. Fig 11 on the previous page shows the simulation results of system model 2.2. The overall consumption from the grid is now decreased to only 9.72 MWh, a reduction of 1.5 MWh or 13 % compared to the grid usage of model 2.1. These savings include the efficiency improvement of the scalable DC/DC converters from the first scenario.

The main differences between fig 9 and fig 11 are to be seen in the graphs in the top parts of both figures. These graphs show the total power demand in time and are on the same scale. The power band in fig 11 is on a yearly basis narrower, meaning that the instantaneous power demand from the grid is less, when households share their PV-power source on the same 350 V DC bus. The privately generated electricity is thus better used, needing less power from the grid. Compared to the simulation in fig 9, this is a reasonable yearly saving of 1.5 MWh. This does perhaps justify higher costs of a larger dynamically scalable converter, to be placed in a central position within a building or HOA.

6. Conclusion and Discussion

As described earlier in this paper, the study was focussed on answering two research questions:

- Does a centralized and dynamically parallel operated DC-DC conversion offer efficiency benefits compared to a decentralized lay-out?
- Does a centralized PV-system offer benefits compared to a similarly dimensioned but decentralized PV-power supply?

The simulations in our research have shown that the place of DC-DC converters in a DC-Grid model has an impact on the energy-efficiency of these DC-Grids. Groups of households, as in Home Owner Associations, are offered improved energy efficiency, when equipped with a centralized dynamically parallel operated DC-DC converter as in model 1.1 instead of five decentralized DC-DC converters, one for each household, as in model 1.2.

	Efficiency of conversion	Simulated Grid usage street-side (MWh)
Model 1.1 (fig 2)	92.5%	18.09
Model 1.2 (fig 3)	96.6%	17.33

Table 1: results of the first research question

The addition of centralized PV-installation of 6.8 kW peak feeding in after the converter as in model 2.2 boosts efficiency of a DC-Home Owners Grid. Such a system model is 13% more energy efficient than equipping every household with an individual DC-DC converter and some of these households with a similarly dimensioned PV-installation as was done in model 2.1. That is 'simple' sharing of energy without very much added intelligence.

	Simulated Grid usage street side (MWh)	Usage compared to 5 Dutch AC households
Model 2.1 (fig 10)	11.2	62%
Model 2.2 (fig 11)	9.72	54%
5 DC households (model 1.1)	18.09	100%

Table 2: results of the second research question

The potential savings add up to 7.0 MWh, because 5 households normally use at least 16.75 MWh from the grid, in present day AC situation. With Dutch kWh prices of around € 0.21 per kWh, savings can add up to roughly € 1,450 per year for 5 households. It does seem likely, that for a period of ten years, € 14,500 will cover both the investment in PV-panels and the surplus in costs of a dynamically scalable DC-DC converter.

The benefit of a centralized converter lay-out alone appears to contribute less to this benefit then the use of a PV-installation feeding in to a 350 V DC bus after that centralized converter. Looking at these savings from the perspective of solar energy however, places that contribution in another perspective. Because adding only the PV-installation to these distribution systems, without the centralized, scalable DC-DC converter will enable savings of 5.5 MWh instead of 7.0 MWh with the scalable converter in place. So adding the centralized, scalable DC-DC converter enables an extra saving of 1.5 MWh for these 5 households, 21% more savings in this simulation. That is a much bigger impact than the efficiencies of the converters alone (92.5 % vs 96.6%) seem to suggest, based upon the simulations of the first set of system models.

Another way to look at these results is the impact this centralized converter and PV-system have on the Grid itself. Five households connected to the grid with an individual DC-DC converter take up more than 18 MWh from the grid, whereas the most centralised model will take up only 9.7 MWh from the Grid. The potential reduction in energy taken from the grid is then 8,3 MWh when choosing a setup with a centralized DC-DC conversion and a 6.8 kW peak PV-installation feeding in after the converter. That 8.3 MWh is more than 45% of the total consumption of these five households put together.

Is it then so that a DC distribution model, where 1400 V DC is distributed and per block of five households or per Home Owners Association converted to 350 V DC for in-house distribution and with a relatively small PV-installation of 1.36 kW peak-power per household will enable a saving of 8.3 MWh in electricity used from the grid? When in single use in a typical household, that same PV-installation will yield in the Netherlands anywhere between 6.1 MWh and 7.48 MWh in present-day operated AC-Grids? That is certainly something that needs further looking into.

But if this result can become part of a new reality, then Dutch government policies are correct in seeking help from Home Owners Associations and small energy collectives in making the future energy supply and distribution in the Netherlands more sustainable and de use of Direct Current distribution grids is the enabler to do just that.

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Presenter: The paper is presented by Pepijn van Willigenburg.