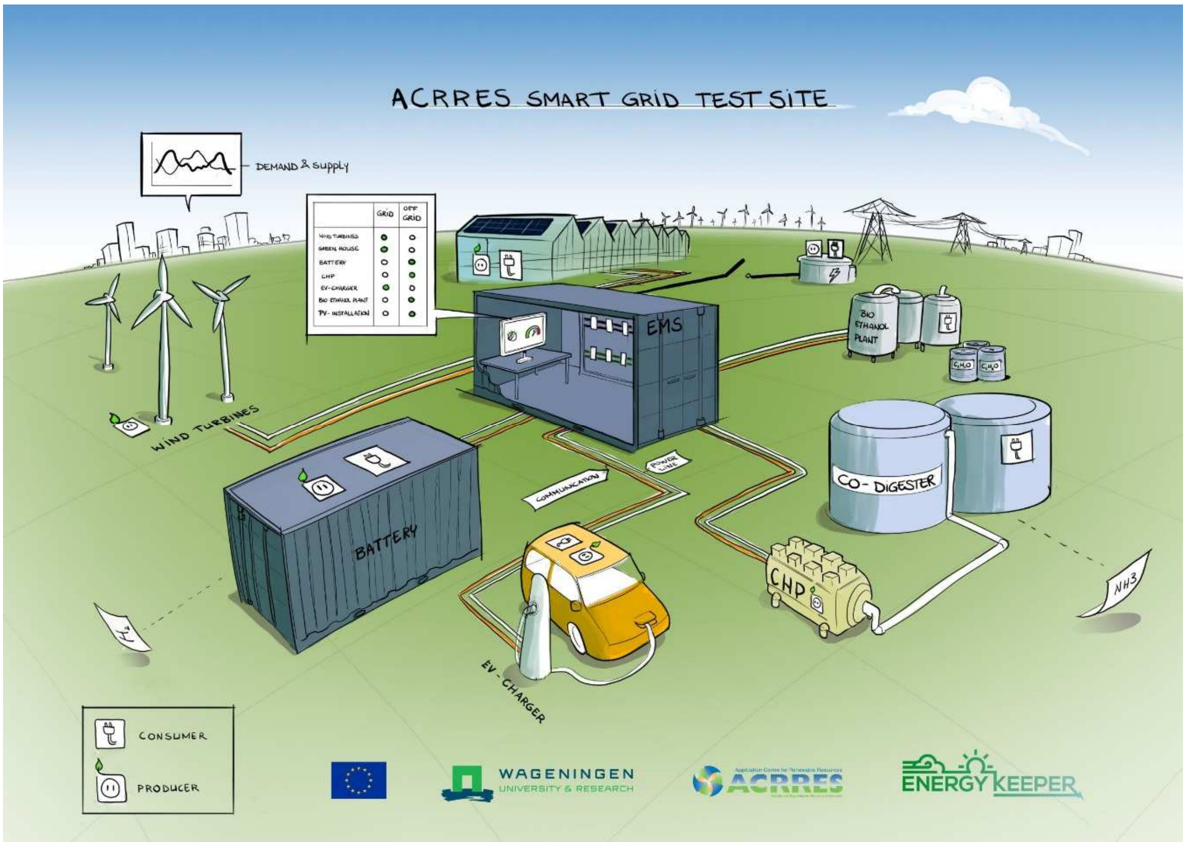
Cellular Smart Grid Platform

Description of ACRRES smart-grid test site and Alfen TheBattery

Sander Huurman[1], Arne Kaas[2], Andries Visser[1], Marcel van der Voort[1], Evert Raaijen[3], Jos van der Burgt[4]



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Summary

To keep global warming below 2^0C, the Dutch government has the ambition for the year 2050 that all energy used will origin form renewable energy sources. To be able to handle 100% renewable energy the current energy system needs to become more intelligent. The introduction of smart-grids is needed to be able to manage the production, consumption and storage of energy.
The smart-grid test site was built as a logical evolution of the ACRRES (Application Centre for Renewable RESources) facilities. This extension introduces the next level of test and research options for renewable energy, complementing the facilities already present facility that focus on circular processing, nutrient recovery, biorefinery and green gas. The addition of the smart grid adds the possibility to integrate the renewable energy processes with already in place using sophisticated energy management. The test site comprises various energy producing and consuming devices which are connected to an energy storage device, for the CSGriP project the energy storage device was the Alfen TheBattery. The whole system is under the control of the Energy Management System that realizes grid stability in both on- or off-grid operation. The test site has the goal to realize the next step in energy management and thereby facilitates the transition from a fossil to a renewable energy based world.
Wind and solar production are not stable and controllable: there is often too much or too little. In addition, the number of providers of renewable energy is growing. There is therefore a need for flexibility to preserve the grid, and for buffers in the form of batteries (to allow excess power to be stored) and biogas (to guarantee a certain level of production when renewables run low).
One way to do this, and tested within the CSGrip project, is through frequency control. A technology which allows demand and supply to be better coordinated through the frequency in the power grid. Supply and demand are currently matched by computers communicating with each other (via ICT technology). The first test at the facility will be to see if ICT can be replaced by frequency control, which should make microgrids much more stable and easy to restart in the case of power outages. The frequency control was tested at the smart-grid test site, in on- and off-grid situations.

1 Introduction

The goals are clear; in the Paris climate agreement more than 170 parties ratified the goal to keep global warming well below 2^0C above pre-industrial levels. Aiming at a maximum temperature rise of 1.5^0C a country such as the Netherlands needs to reduce its carbon dioxide (CO_2) emissions by >100% in 2050, in 2030 already a 40-50% emission reduction (compared to 1990) must be achieved. The utilization of renewable energy sources is a great opportunity that could lead to drastic reduction in CO_2 emissions and fossil fuel consumption. The transition from fossil to "green" energy sources comes with its own challenges[2]. Moreover, the introduction of renewable resources can lead to a mismatch in power supply and demand. In some cases renewable energy sources that display variable power production lead to grid instability and, in worst case scenarios, could generate a grid blackout[3]. The more distributed nature of renewable energy sources creates another challenge in fully utilizing renewable energy sources[4].
The transition towards energy systems fully depending on renewable energy sources requires technological transformation of the power system. An important step in system transformation is the introduction of smart-grids. Using communication between power producers and consumers is needed to manage the production, consumption and storage of energy and thereby balancing and stabilizing power grids[4].

2 CSGriP project and ACRRES smart grid

The Cellular Smart Grid Platform (CSGriP) project aimed to make the electricity grid more reliable by using the grid frequency as communication signal between autonomous cells. By using the grid frequency as a control signal for prosumers (i.e. producers and consumers), no other communication (central or external) is required for safe and reliable operation (e.g. during grid failures, IT infra-structure failures or intended island operation). Renewable Energy (RE) producers and flex consumers are programmed to react to the grid frequency which is determined by local battery inverters of the cells.

The grid frequency of a cell represents the cell health status, where:

- low frequency means an energy shortage: no RE production, high load and/or empty batteries.
- high frequency means an energy surplus: lots of RE production, low load and/or full batteries.

In the CSGriP project the control principles for cell operation and interaction, based on the local grid frequency, have been developed, modelled and simulated. Experiments were performed at ACRRES.

At the Wageningen University and Research wind and solar test site in Lelystad (ACRRES test site) a full functional smart-grid is realized to be able to simulate and test limitless power distribution scenarios by combining different renewable energy sources with different consumers and storage devices. The battery and energy management system (EMS) play a key role in the test site grid, the EMS has the ability to switch each connected device seamlessly to an on- or off-grid circuit, while both circuits maintain fully functional. In the off grid circuit a battery plays an important role of long term energy storage. Grid stabilization, both on- or off-grid, by absorbing pike loads and filling up power gaps can be an additional smart-grid function of a battery. In addition to power storage or buffering, switching the battery directly to the grid opens the possibility to trade energy on the different energy markets.

Photo: ACRRES smart-grid test site

Using high frequency monitoring the EMS continuously observes the system and decides which device should be ramped up- or down or even switched on- or off in order to maintain grid stability. In addition it monitors and adjusts the batteries state of charge (SOC) depending on test or simulation settings. Device control takes place by power line frequency control, but direct (2-way) communication between devices and the energy management system (EMS) is also possible.

The ability to switch connected smart-grid devices to a different grid circuits makes it possible to test different on- or off-grid scenarios simultaneously. In addition, the EMS can be programmed to set device priorities based on energy availability. For example, when solar and wind energy provides the required energy consumption the power delivery from a combined heat and power unit (CHP) needs to be down regulated in order to save biogas. In addition, the charge rate of an electric vehicle can be maximized during maximum solar and wind power delivery, while the charge rate is downgraded or even stopped when there is an impending power shortage.

3 CSGriP functionalities

The CSGriP cell is a microgrid that can operate in island mode or in grid-connected mode. In island mode the cell needs to maintain frequency and voltage, independent of the changes in power supply and demand. The battery inside the cell can absorb surplus power or provide power in case of shortage. At the same time, the battery converter controls the cell frequency and voltage. In the CSGriP concept, the frequency is the main communication signal between the cell and the grid and also between multiple cells. This means the system will keep on operating in case the central communication infrastructure is lost.

The information of the cell freqency is in the deviation from the normal value of 50 Hz:
The grid frequency of a cell represents the cell health status, where:

- low frequency < 50 Hz means an energy shortage:
  no RE production, high load and/or empty batteries.
- high frequency > 50 Hz means an energy surplus:
  lots of RE production, low load and/or full batteries.

The deviation works in two ways:

- depending on the state of charge (SOC) of the battery, the battery system will set a frequency offset (with a linear relation to the SOC):
  - up to 2 Hz if the SOC is high;
  - down to -2 Hz if the SOC is low;
- the frequency controller uses droop control to adapt the actual frequency to the power output of the battery. (If there is balance between demand and supply in the cell, the power of the battery is low; if there is either too much demand or too much supply, the battery power is high.)
  - if the discharge power of the battery is high, the frequency will decrease according to the droop curve, signalling a shortage of power;
  - if the charge power of the battery is high, the frequency will increase according to the droop curve, signalling a surplus of power;

Producers and consumers in the cell respond to the frequency deviation by decreasing or increasing power, which will cause a stabilising change in frequency.
At the same time, also other cells may respond to the frequency deviation of this cell. This is done by synchronising to the cell with a large frequency deviation and sharing the power between the cells.

Because one CSGriP cell was available, most of the functionalities tested were island mode functions related to the frequency response by all components in the cell. These components are:

- battery system and frequency control system
- wind turbines
- solar PV panels
- CHP plant
- controllable loads (EV charger and others)
- non-controllable loads

4 Test site components

4.1 General background test site

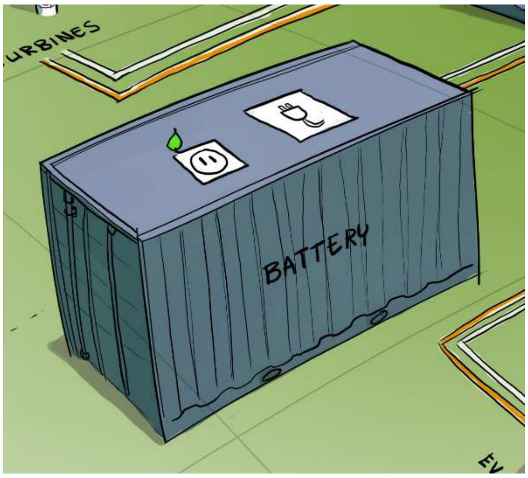
The smart grid test site was built as a logical evolution of the ACRRES (Application Centre for Renewable RESources) facilities. This extension introduces the next level of test and research options for renewable energy, complementing the facilities already present that focus on circular processing, nutrient recovery, biorefinery and green gas. The addition of the smart grid adds the possibility to integrate the renewable energy processes with already in place using sophisticated energy management.

The smart grid test facility is large enough to test and simulate real life scenarios but still small enough to have full operational freedom without restrictions. The ability to run the system in full off-grid mode, on-grid mode, or a mix of both, for extended lengths of time when required, creates a fully independent environment with its own specific testing possibilities. Because the smart-grid's EMS can be programmed in virtually limitless possible ways it is possible to test and simulate scenario's that can lead to improved insight in grid balancing and stabilisation. In other words, the ACRRES smart grid test site is an ideal location to test complex energy management algorithms, develop of new grid balancing tools, test device behaviour in smart grids, comparing battery prototypes, test maximized grid utilization and balance and much more.

The devices at the ACRRES smart grid test site can be used not only as energy driven components but also in, non-battery, "energy storage" processes, collectively called "power to X" (PTX). The production of hydrogen by electrolysis of water or steam reforming of bio-methane is are example of PTX. The produced hydrogen can be stored and, later, be used for different applications, for example in fuel cells to generate electricity or it can be sold as a product to different industries. Another example of PTX is the production of the nitrogen fertilizer nitric acid from bio-ammonia stripped co-digesters.

The smart-grid exists out of several components that produce or consume energy. Like mentioned before, the core of the off-grid circuit is a battery and energy management system. Currently (2017) a lithium-ion battery is tested in a grid setup where in case of a network blackout a decentral network cell is switched to off-grid mode and is able to operate independently until network functionality is restored. In the Energy Keeper project (started in 2017) an organic redox flow battery will be developed and tested in the smart-grid system.
Within the smart-grid, wind turbines, photovoltaic cells and a combined heat and power unit running on biogas produce electricity. Energy consuming components on the other hand are: algae raceway ponds, heat-cold storage installation, bioethanol plant, co-digesters (biogas production), compressed natural gas installation and an electric car charging pole. The smart-grid is designed flexible enough to add new or other devices easily.
Each component currently installed in the smart-grid is described in more detail in further paragraphs.

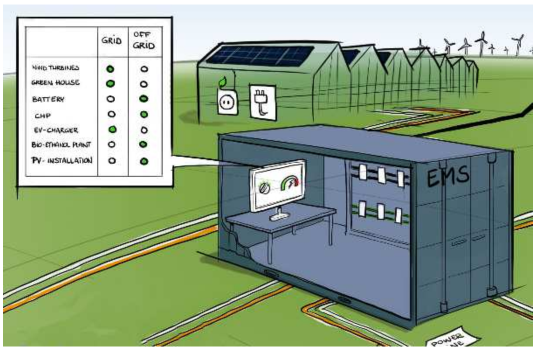
4.2 Energy storage



Energy storage devices, like batteries, can either absorb (charge) or deliver energy. These properties can be utilized to run a battery in different operational modes, for example: buffer mode, storage mode or a mix of both. The storage mode is mainly intended to store energy in larger amounts for a longer period of time while the buffer mode stores energy peaks and delivers energy when small energy shortages occur. The test site can be utilized not only for “plug and play” batteries, but also for the development of new battery concepts, like for example organic redox flow batteries.

The batteries “state of charge” (SOC), the filling level of the battery, can be controlled in many different ways. In an off-grid situation the weather forecast combined with a low SOC could for example postpone energy production by the CHP when enough sunshine or wind is expected and visa versa. In an on-grid situation the SOC of the battery could be lowered, by for example charging EV’s directly, prior to a period of abundant solar power, the battery could be used as a buffer, to store energy or both. The way a battery is used in a smart grid is very versatile, is smaller, private home grids, battery behaviour could even be connected to personal agenda’s to make sure enough renewable energy is stored to charge an EV for the next trip. Trading energy on a marketplace (for example: APX) could be another interesting application of batteries in smart grids. This application will also be tested at the test site.
Within the CSGrip project the energy storage is supplied by Alfen (TheBattery). TheBattery is the center of the test site. The specifications of TheBattery supplied by Alfen are highlighted in chapter 4.

4.3 Energy management system



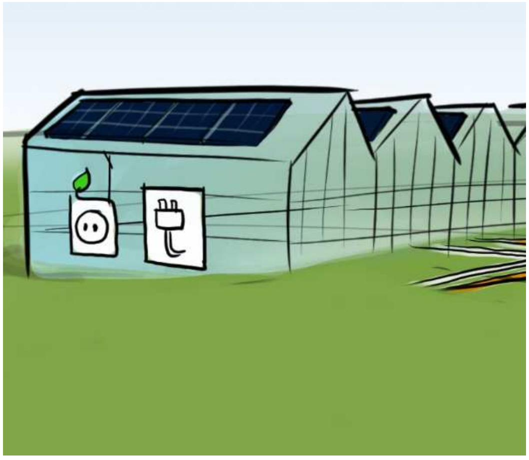
At the test site each individual component or component group is connected directly to a switch unit. Within this unit the components can be switched to the grid or off-grid circuit, switching is managed by the EMS based on for example programmed device priority or test and validation scenarios. The brain of the EMS is a programmable logic controller (PLC). Specifically for the CSGrip project is that TheBattery of Alfen is in control. The EMS performed the actual switching are a signal by TheBattery. This as safety buffer for the smart-grid test site.

4.4 Energy producers

4.4.1 Wind power

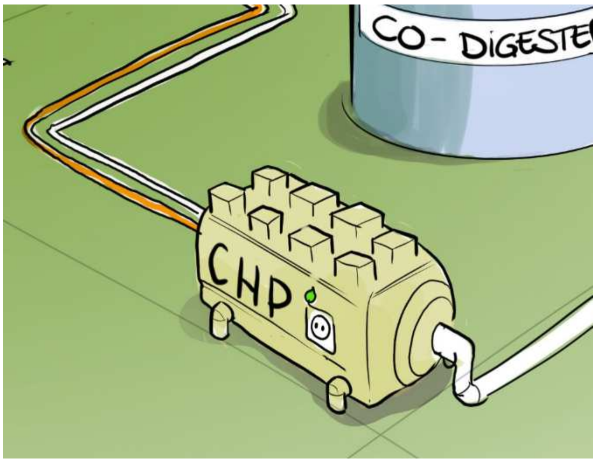
At the test site 3 wind turbines are realized and directly connected to the grid infrastructure. The turbines are manufactured by Bestwind and have a power output of 10 kWp AC per turbine. The turbine sits at a height of 10 meter. Energy production can be controlled by using grid frequency, the turbines inverter listens to the grids frequency and can react to it in the desired, programmed, fashion. Also the turbines can be controlled via a Modbus connection over TCP/IP. Having control over the turbines power production in multiple ways makes them very useful to simulate various grid scenarios, from trying to balance a grid as smooth as possible to test the grids blackout response.

4.4.2 Solar power



The power of the sun can be converted to electricity using solar panels. At the smart-grid test site 63 panels (250 Wp/panel) are mounted on the rooftop of a greenhouse. An SMA sunny tripower 15000tl inverter converts the generated solar DC to AC power and feeds it to the grid. The power production and panels behaviour is controllable in exactly the same way as with the wind turbines. When charging the battery directly from the solar panels, the DC/AC power conversion in the solar inverter and the AC/DC conversion on the battery side can be bypassed, greatly improving power efficiency.

4.4.3 Combine Heat and Power



The potential of manure as sustainable energy source is continuously tested and optimised at the ACRRES test site. Currently two 500m^3 co-digesters are optimized to run on cow manure and grass from nature areas. The produced biogas is mainly used to generate heat and electricity via a combined heat power unit (CHP). A small fraction of the produced biogas is used to research and optimize bio-methane storage solutions, mainly focussed on bio-CNG and bio-LNG production and storage.
The installed CHP has a maximum power output of 125kWh electric and 250kWh thermal. The residual heat and flue gas is used to support several other processes like algae cultivation, bioethanol production and support heating.
CHP power delivery is based on grid frequency and biogas availability. When a higher grid frequency is detected the power delivery is reduced. In addition when the gas pressure in the co-digesters reaches an under control limit the CHP is shut down. Frequency based CHP regulation can be set to a higher priority compared to, for example, wind turbines or solar panels in order to safe biogas for windless or sunless periods. Practically this means that when the grid frequency increases the power delivery of the CHP is the first source that is reduced of shuts down. For testing purposes the frequency controlled production can be overridden by a 4-20mA signal which regulates CHP power between 50% and 100%.

4.5 Power consumers

4.5.1 Biomass digester group

A biomass digester can convert organic materials into biogas, methane (CH_4) and carbon dioxide (CO_2), under anaerobic conditions. At the ACRRES test site two biomass digesters run as manure co-digesters that are currently optimized to produce biogas from cow manure and nature grass.

4.5.1.1 **Molaris pre-treatment**

The use of nature grass requires additional pre-processing to optimize biogas production. At the ACRRES test site an electrically driven Molaris hammer mill shreds the grass stalks to smaller bits, this increases the surface area which increases the gas production. In addition an electrically driven rotary cutter adds an extra particle size reduction step during the digestion process. The Molaris hammer mill is passive energy consumer.

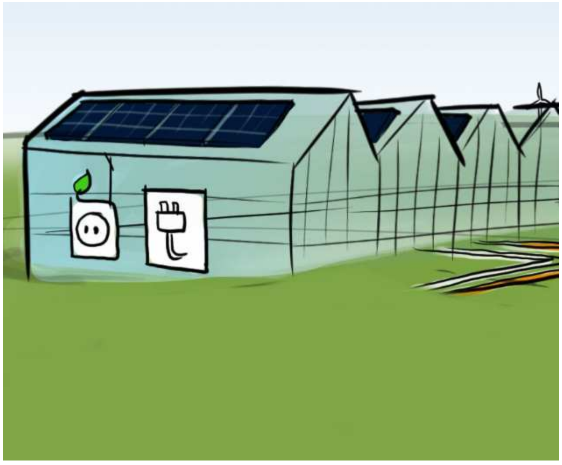
4.5.1.2 **Biomass co-digesters**

The manure and nature grass mixture must be mixed continuously to ensure a homogenous process and a stable gas production. Produced biogas is mainly used to produce electricity, see above, paragraph CHP. The mixers and auxiliary devices are passive energy consumers

4.5.1.3 **Bio-LNG and Bio-CNG production**

In a scenario where solar- and wind energy is abundant and biogas reserves reaches >100%, surplus produced methane can be stored in a compressed gaseous of even liquefied form. Both storage ways could function as a methane battery to supply the CHP in times of methane shortage. Using methane as a transportation fuel is another possible application. Both storage technologies are passive energy consumers.

4.5.2 Greenhouse group



The greenhouse located at the ACRRES test site is used as a multipurpose building. The greenhouse is equipped with different aquatic biomass cultivation options and hardware to process the cultivated materials. The cultivation equipment ranges from simple plastic pond to full monitored raceway pond and vertical LED algae ponds. A heat and cold storage device installed in the greenhouse is able to prevent overheating of running research in summer times. The greenhouse functions as a passive power user.

4.5.2.1 **Racetrack pond**

Growing micro algae as a source of proteins or chemical components is also tested at the facility. There are different ways to cultivate algae, one of the systems running in Lelystad is a raceway pond. Basically it is an oval shaped shallow pond in which the algae culture is mixed horizontally. Residual heat from the CHP is used to increase the cultivation temperature in colder periods of the year, in addition CHP flu gas is used to increase the CO_2 level in the pond and regulate the pH. A submersible electric thrust mixer is used for horizontal culture displacement and mixing. Various mixer loads can be used to test grid behaviour. Raceway pond power can be varied manually, no grid based response and control available.

4.5.2.2 **Heat-cold storage (HCS)**

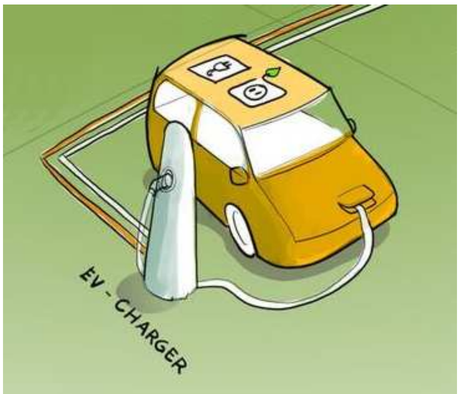
Various biological processes require thermal regulation. For example, algae cultures using artificial light tend to build up heat, cooling is required to stabilize the culture temperature. At the test site HCS is used to store heat in summer and cold in winter, the stored cold can be used in summer to cool processes and visa-versa. The HCS at the test site uses polyethylene pipes drilled to a depth of 100 metre, the soil column surrounding the pipes is used as a buffer zone for heat or cold. Electricity is used to retrieve either heat or cold form the depth, depending on heating or cooling demand the grid load varies, no active grid based response and control available.

4.5.3 Bioethanol plant

Originally the bioethanol plant on the ACRRES test site was designed to run on corn. In the pre-treatment soak tank corn starch is converted to monosaccharides with the aid of enzymes. The mash is then used to produce bioethanol as a bi-product of anaerobic yeast metabolism. Recently the plant is adopted to be able to run on raw sugar beet mush. Sugar beets are lightly cleaned, ground down to a particle size of approximately 2-4 mm, this mush is directly used as the food source for an active yeast culture in order to produce bioethanol. This adaptation could lead to a more sustainable processing method by reducing the energy input for bioethanol production. Alternatively this, direct processing, method could also be used to produce other industrial chemicals.

The bioethanol plant includes; 2 stirred fermentation tanks with a volume of 1.5m^3, drum sieves for coarse separation, stacked disk centrifuge for fine particle removal, distillation column including bioethanol storage and several auxiliary devices including detailed process control and data logging. Residual products from fermentation are fed to the biomass digester. Residual heat from the CHP is used as heat source for: bioethanol building heating, the distillation process and the corn soaking process. Related to the smart-grid, the build-in tank stirrers can be used to vary grid load. Stirring speed is controlled by using a 0-10 Volt signal from the EMS fed in to a local PLC.

4.5.4 EV Charger



Electric or hybrid cars can, when using sustainable energy, contribute to the reduction of greenhouse gas emissions by decreasing the demand for fossil resources. When plugging a car in a smart grid the car's battery can be used to store or deliver energy, basically the car functions, up to a certain level, as an energy buffer.

The behaviour of the EV charger and car's battery can be controlled using grid frequency and a 0-10 volt signal. Depending on the desired behaviour the SOC of the car's battery can be regulated based on planned travel distances, market energy prices or local energy availability.

5 The Battery

5.1 Technical setup and description of battery and frequency control in island operation

The grid forming battery (TheBattery - Li-Ion battery with variable frequency inverters) is programmed in such that in island operation it changes its frequency based on the SOC and the current power output and on a droop curve. With this behaviour, TheBattery can stabilize the grid, by indirectly controlling the power output-consumption of connected pro-consumers. The base frequency of TheBattery changes from 49,80 Hz 51,2Hz in three linear windows. At 0% SOC the frequency is 49,8Hz from which it increase to 49,8 Hz at 30% SOC. The normal operation window is from 49.8 Hz to 50,2 Hz at 80% SOC. Above the 50.2 Hz the frequency increases to 501.5 Hz at 90% SOC and to 512 Hz at 100% SOC. The droop curve of the battery is shown below.

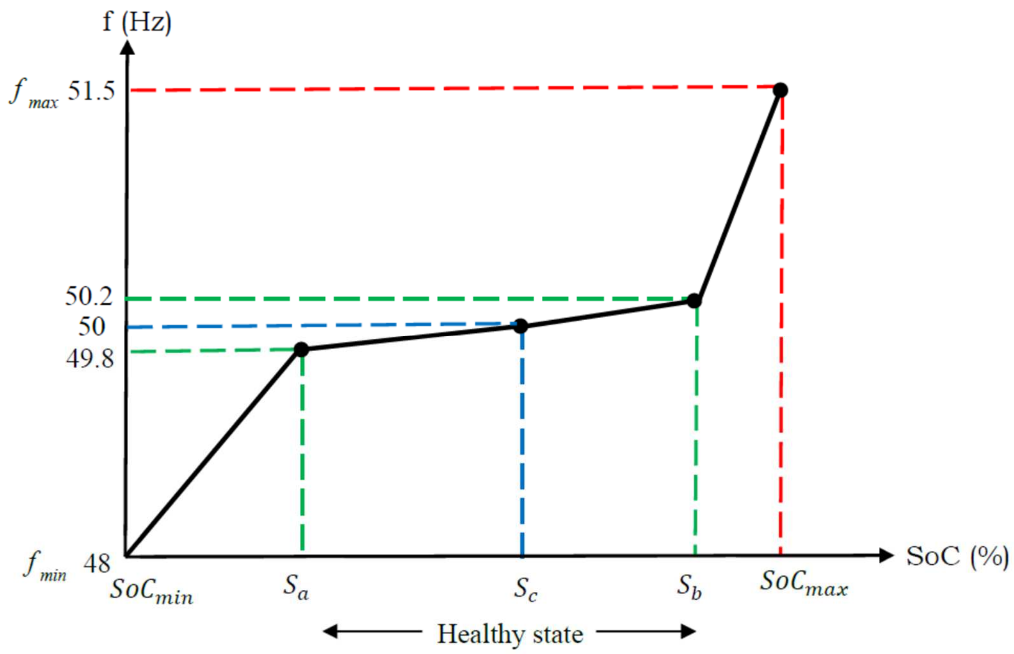


Figure: Droop curve TheBattery

In grid connected mode the frequency of the grid is leading, in island operation the battery is leading according droop control above which is fully customizable. This is needed if working with existing equipment which not has full frequency capability. More detailed information is given in the test report.

6 CSGriP test results at ACRRES

6.1 The test plan

A CSGriP cell controls the grid frequency to regulate the power settings of consumers and producers in the cell with the aim to maintain the energy balance within the cell's local LV grid. When the cell is connected to the main grid, the frequency cannot be controlled by the cell, therefore its unique behaviour cannot be tested. Most tests were therefore performed in island mode, so the battery could control the grid frequency and would thereby regulate the prosumers.

The first test was to verify that the behaviour of TheBattery was according to specification, by cycling the battery over the full SOC-Power envelop. This means TheBattery was tested at power levels up to ± 176 kW (3x250A) at each SOC. During this test the frequency was observed and compared to the programmed behaviour.

Secondly, all components in the test site were verified to operate as they should with the variable frequency: all individual devices (groups) were tested in island mode, where the frequency was varied over the full CSGriP frequency range, i.e. 48 Hz tot 52 Hz.

Thirdly, the load disconnect/switch control of the EMS was tested for each group. This test included a grid failure test, which was activated by the EMS. In this test the grid switch was suddenly opened and it included a grid reconnect by automatic synchronisation of TheBattery.

Finally, a duration test with all components connected to the battery bus was performed in island mode, to check if any bang-bang behaviour would occur.

6.2 Lessons Learned

The CSgriP principle works as intended: all prosumers responded to the variable grid frequency according to their programmed operation. There were no major problems in maintaining energy balance, not even during grid failures tests.

A few technical issues were encountered during the testing. The CHP system showed some voltage instability. The solar PV system could only be tested in a very limited way, because PV output was very low (Dec. 2017).

Interaction of the CSGriP cell with the main grid was tested. Interaction between two CSGriP cells could not be tested, because only one cell was available.

Because the CSGriP battery is a containerised device, this could be turned into a mobile solution: A battery on a truck could be utilised by grid operators, for example, to resolve a grid failure with a short response time in a sustainable way. The mobile battery could then work together with local renewable energy sources or with an emergency generator. This mobile battery could also be used to support weaker grid areas where prosumers overload the grid connections during certain periods of time in a year.

The CSGriP concept could be a stepping stone to an international standard. Presently, not all prosumers respond to the grid frequency for power control. It is recommended to implement a standard that requires and defines response to grid frequency changes by larger energy users and consumers, such as: washing machine, dryer, refrigerator, EV, CHP, PV, electric heatpump, HACS (heat and cold storage), etc. A price incentive for support during grid frequnency deviations should be determined (e.g. by grid operators) in addition.

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