What happens when algorithms take control of the charging of electric vehicles on a massive scale?

By: Knowledge and innovation center ElaadNL

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INVADE

Elaadnl

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Summary

In this paper we want to share our findings and lessons learned during a large scale Smart Charging pilot we did on 1,000 charging points (700 stations) all over the Netherlands. In the pilot, which was part of the European INVADE H2020 project, we virtually divided the 1,000 public charging stations of CPO EVnetNL over two actual neighborhoods. Both do not use natural gas for heating homes anymore. By virtually adding big numbers of charging stations and charging EV's, we could take a peek into a future where nearly all cars are electric resulting in an increasing peak demand on the power grid during peak hours at the end of the working day when everybody comes home.

The idea is that by steering the power demand of EVs (that is: Smart Charging) the grid won't be overloaded. To not cause any disturbance for the drivers our specially developed Smart Charging algorithms made only a small adjustment in the speed of charging. Even with this small adjustment in charging speed we were successful in staying within the limits of the grid during summertime. But during winter, when there is more demand for electricity not only for heating, lights et cetera, but also of EV's themselves, more adjustments will be necessary in our future scenario.

As the connection time (the car is plugged in) is most of the times longer than the actual charging time, especially in the early evening when most Smart Charging is necessary, there is still a lot of room for using Smart Charging algorithms to prevent overloading of the grid. Also, if more data gets available via open standards in communication between EV's, Charging Stations and back end servers, more fine tuning in Smart Charging will be possible.

If we can add information about for example the state of charge of the batteries, we can prioritize between cars. Thus in the pilot we already proved large scale Smart Charging is possible and that it can help management of the power grid, and also showed the way how to use the full potential of Smart Charging. Also we can conclude that Smart Charging will be necessary in an *all-electric* future, especially during wintertime.

Introduction: electric cars as part of a sustainable energy system

We are on the eve of a major mobility revolution. In a relatively short period, we'll switch from petrol and diesel to electric driving. One of the key Paris 2015 climate agreements is to reduce transport emissions. In the Netherlands, this key message was translated by the coalition government into the following aim: by 2030 all new passenger vehicles must be emission-free! At the same time, electricity production is changing dramatically from fossil fuels like coal and gas to renewable sources like sun and wind.

One could say that we are in the middle of the third power revolution. In the first one the electric light bulb replaced the gas lamp. Reliable, safe and clean light entered our households in the late nineteenth and early twentieth century, reducing our dependency on daylight for both work and life. The second power revolution was the arrival, halfway through the twentieth century, of household electrical appliances.

These electrical appliances quickly became mainstream: the fridge, freezer, washing machine, iron and vacuum cleaner. As a result, housework was no longer a day's work, but our dependency on electricity increased. And in this storyline we are now in the middle of the third power revolution with the introduction of solar panels on our roofs and electric cars on our driveways. So we are becoming prosumers: we're starting to generate and store electricity ourselves, for example in our electrically powered cars.

The one million dollar question is: how can we smoothly and sustainably charge millions of electric cars? Contrary to what might be expected, the growth of the number of electric cars is not only a challenge for the energy system, but also part of the solution.

Smart Charging

The solution for the charging needs of electric vehicles lies in using Smart Charging. Smart Charging is essentially a control signal that indicates when and at what speed an electric car is charged. Smart technology ensures that charging takes place at the best time and at an optimum speed, for example, when there is sufficient sustainable electricity from the sun and wind or by charging outside peak hours. With Smart Charging, the demand for electricity from an electric car is always adjusted to match the drivers needs, as well as the needs from the energy system. It does this in such a way that there's always enough power to meet the demand.

A further advantage of Smart Charging is that the car can be used for energy storage for purposes other than driving. This means that you not only use stored power as required by the car for driving, but that your car acts as a power supply for other usage than driving. This technique is commonly referred to as V2G (Vehicle to grid). The power stored in your car can, for example, be used to power your own home, the neighborhood or even fed back into the grid.

Using all available sustainable energy

So let's explore the first possible optimization a little bit further: using all available production of sustainable energy. Because you can't influence the amount of sunshine and wind, you need a much greater capacity to always ensure enough power compared to electricity production through traditional power plants; the latter can always step up production if demand requires it. The need for high capacity solar and wind production units has a downside. There will be certain moments at which energy production is so large that it exceeds the energy demand.

In Germany this already happens from time to time. There, electricity prices can become negative. In these cases, German power consumers are paid to use electricity: a bit of a topsy-turvy world. A long period of overproduction, without means to transport electricity abroad or increase consumption, can lead to the temporary shutdown of solar panels and/or wind turbines. This is called curtailment and although it is needed to maintain the grid, it is actually a waste of sustainable electricity. Fortunately electric vehicle charging allows us to balance the demand for electricity to the supply, called 'demand response'. The way to do this is by operating a Smart Charging regime.

Avoiding congestion

The second optimization Smart Charging can bring to a huge number of electric cars is to avoid overloading of the power grid. When in the near future we'll have millions of electric cars, the can't all charge at full power at the same time. There are two reasons for that: not enough power production for peak demand of EVs and not enough grid capacity to transport all that electricity.

Electricity must be generated at the same time as it is needed. A device that requires a little bit of power each time has a completely different impact on the production capacity than a device that requires a lot of power in a shorter time. Think of a kettle. If a lot of electricity is required in a short time, it must also be possible to generate it at that time.

Electric cars can charge a lot of electricity relatively quickly. If there are large numbers of cars - in the scenario that everyone in the Netherlands drives electrically (more than 8 million EVs) - and they all charge at the same time, the production capacity must therefore also be considerably expanded in order to meet this peak demand. That effect is much greater than the predicted growth in total electricity demand.

In numbers: if 8 million cars are electric and they all started charging at six o'clock in the evening (with a capacity of 11 kW), an additional 88 gigawatt (GW) of production capacity would be required at that time. That is four times as much production capacity as is currently available: we would need to move from the current 31 GW capacity to 119 GW.

This is a very unlikely scenario. To ensure this peak demand, we would have to develop a lot of extra wind turbines and solar parks or keep the old gas-fired power plants running for longer, or even extend them. In any case, it would be an extremely expensive solution, requiring huge investments (think of € 90 billion) for energy production capacity only used for one hour or so a day.

In addition to sufficient power generation at peak demand, we would also have to get this additional power to the right place at the right time. Energy has to be transported via the electricity grid from the production location to the demand site at the moment required. And the electricity grid simply does not have the capacity to transport all the electricity needed without using Smart Charging.

Our Dutch electricity network has a lot of spare capacity. On average, the network load is only 20- 30 percent of the maximum capacity. This is a logical consequence of the fact that our power grid was designed to cope with the highest expected electricity demand. This means that the power grid is only intensively used temporarily at peak times. Outside of these moments, the grid has about 70 percent capacity left, spread across a whole day; that's more than enough to charge all the electric cars. However, if the electricity demand as a result of charging electric cars takes place mainly at peak hours, and if, at that moment, there is a high demand concentrated at certain locations, then a network problem can arise.

Suppose you come home from work somewhere between five and seven o'clock, park the car on the street or on the driveway and start charging. Depending on the make, the car will charge for hours and take 3.7 to 11 kW from the grid (in some exceptional situations even 22 kW). That's much more than an average household with no electric car; an average household has a power demand of between 1 and 1.5 kW. If you're the only one in the street with an electric car, there's no problem; the grid has more than enough capacity for that.

But if you're a trendsetter and the whole street starts driving electrically and everyone charges their cars at similar times, local overload can occur. This causes the underground cables and the transformers to heat up, and can eventually lead to a breakdown. This type of overload mainly arises in the low-voltage network; network operators call this "local grid congestion".

Essentially, there are two ways to deal with this: installing the extra production capacity and additionally add to the network's 'strength', i.e. installing thicker cables and transformers with more capacity, or ensuing a better distribution of the power demand. The first option is not an attractive option for a number of reasons. Firstly, it's expensive. Secondly, the question arises as to whether this is even feasible: the Netherlands has a great shortage of technical personnel and this, combined with all necessary permits will result in unacceptable long lead times. That's why the network managers only want to strengthen the networks in those places where other solutions do not offer sufficient help. So the second option, ensuing a better distribution of the power demand, is a necessary measure and this can be achieved via Smart Charging.

Summarizing, for both using sustainable energy at 100 percent and avoiding congestion in our power system, we need Smart Charging. In other words, Smart Charging is a necessary condition for massive and sustainable electric car charging.

Setup of the large scale pilot

Concluding that Smart Charging is necessary, we need to get as much experience with the technique as possible before we actually have millions of charging EV's in our streets. The European INVADE h2020 project gave us an unique possibility to do so. And not in a laboratory set up (which has been done before) but on a real life large scale pilot.

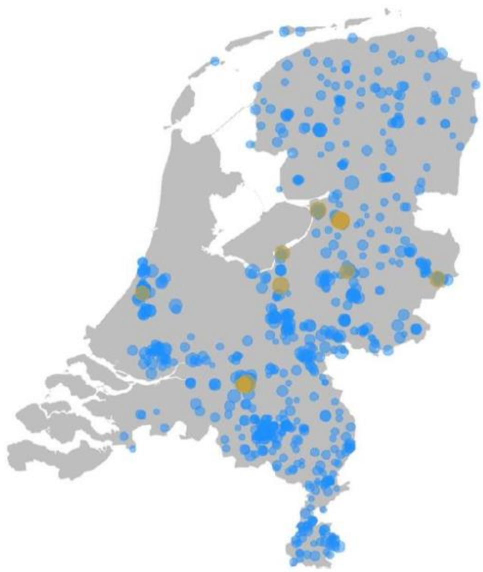
We developed a Smart Charging algorithm that continuously and in real time monitored the amount of charging in relation to the available capacity on the grid (as measured by the local transformer) and tested it with 1,000 public charge points (700 charging stations), operated in the real word. These charging stations were virtually divided into two all-electric modern neighborhoods where large concentrations of electric vehicles are expected in the future (one in the city of Ede (Kernhem, Doesburgsebuurt) and one in the city of Arnhem (Schuytgraaf-Noord)). The aim: to test if we are able to stay within grid limits using a Smart Charging algorithm without hindering the EV-driver experience.

Our algorithm controlled the speed of charging for 160,000 charging sessions. In half of the sessions the speed of charging was adjusted slightly to prevent a virtual overload of the network.

Focus on public charging

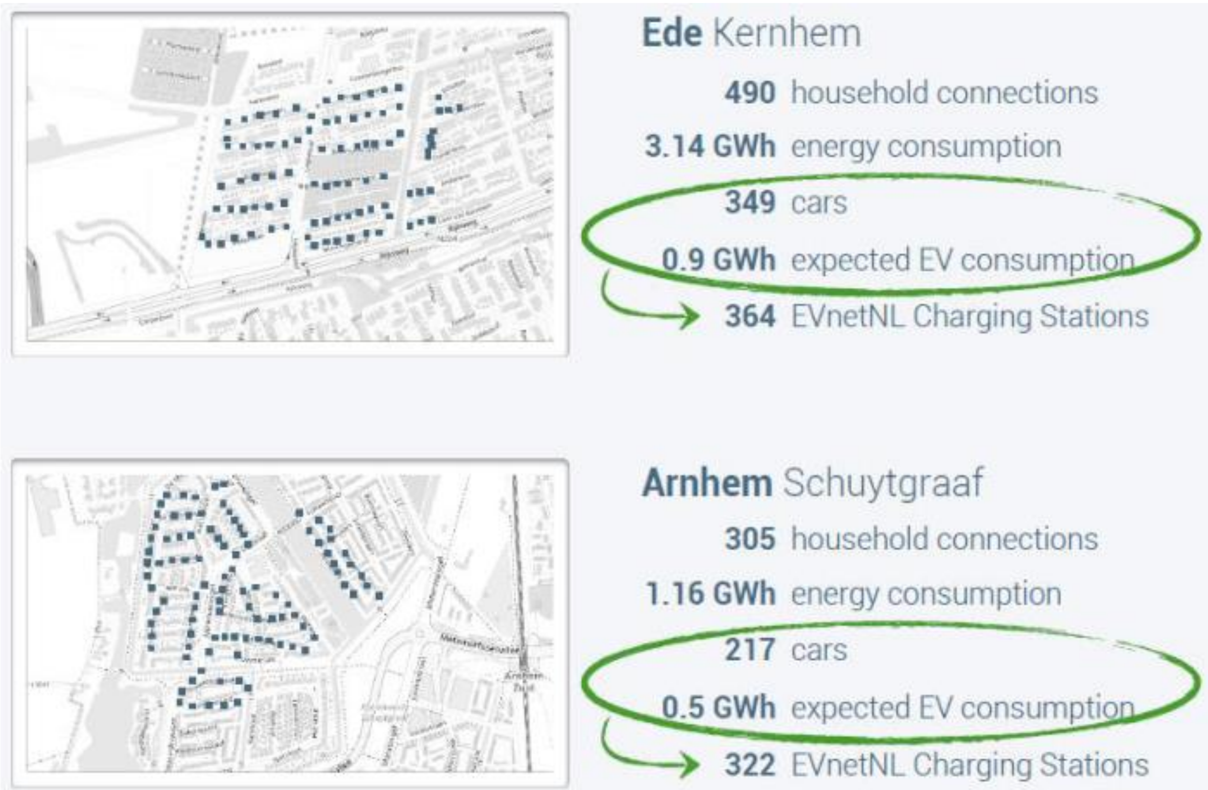
The pilot project was done on public charging stations of Charge Point Operator (CPO) EVnetNL. In the Netherlands, around 26% of charging stations are public chargers, against 74% private or semi-private(at home or at the office). This ratio is reflective of the number of households with a private driveway compared to the number of households cars parked in public space. Public charging has and will continue to have a large impact on the grid in the Netherlands.

The AC charge stations are from a different suppliers, and connected through 3*35A connections. All EVnetNL chargers are Smart Charging ready and have a larger connection than the standard 3*25A connection. All these charging stations support the open communication protocol OCPP 1.6 between charging stations and back offices.



Moving 1,000 charge points virtually

Bron: https://www.schuytgraaf.nl/huren-aan-de-dijk/



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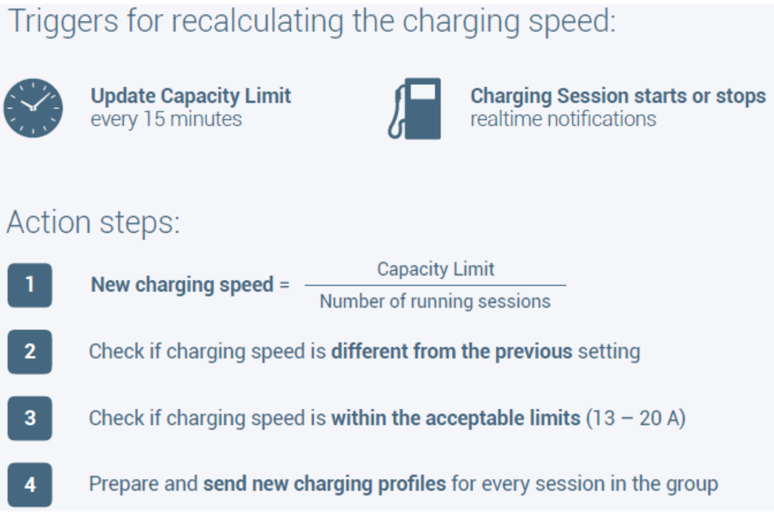
Designing the Smart Charging algorithm

Foto: Nynke Arends

In the design of our Smart Charging algorithm we had to take into account the possible impact of our actions on driver experience. Our estimation was that a lower boundary of 13 Amperes would allow us to see the impact of smart charging without too much impact on driver experience, since this is a familiar and therefore acceptable speed on regular dual socket charging stations.

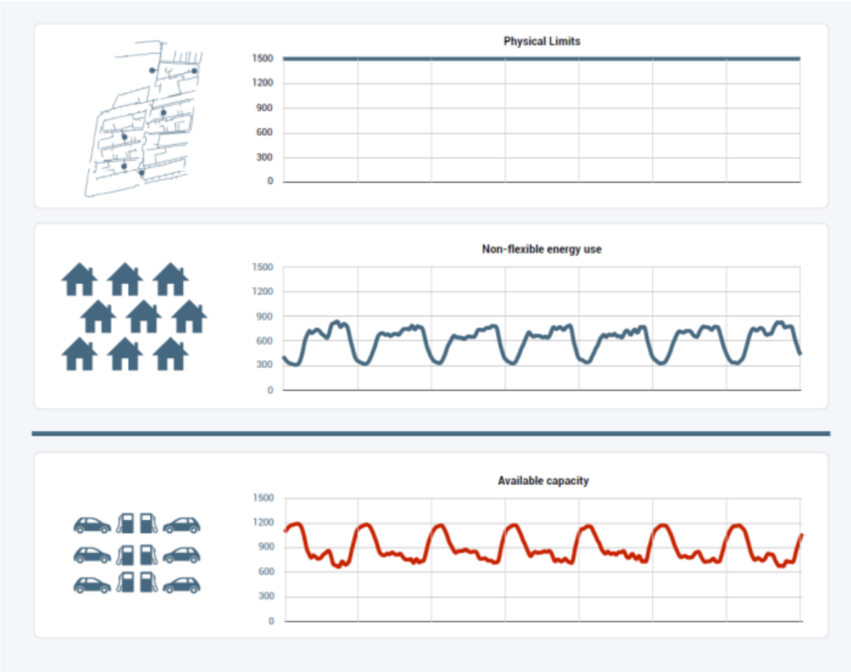
The Smart Charging algorithm



In the algorithm the triggers for recalculating the charging speed are either the update of the capacity limit (every 15 minutes) or the start or ending of a charging session. The actions following a trigger are:

- calculation of the new charging speed (based on the capacity limit and the number of running sessions);

- check if the new charging speed is different from the previous charging speed;
- check if the proposed new charging speed is within acceptable limits;
- send new charging profiles to all sessions (all sessions are updated in charging speed equally).



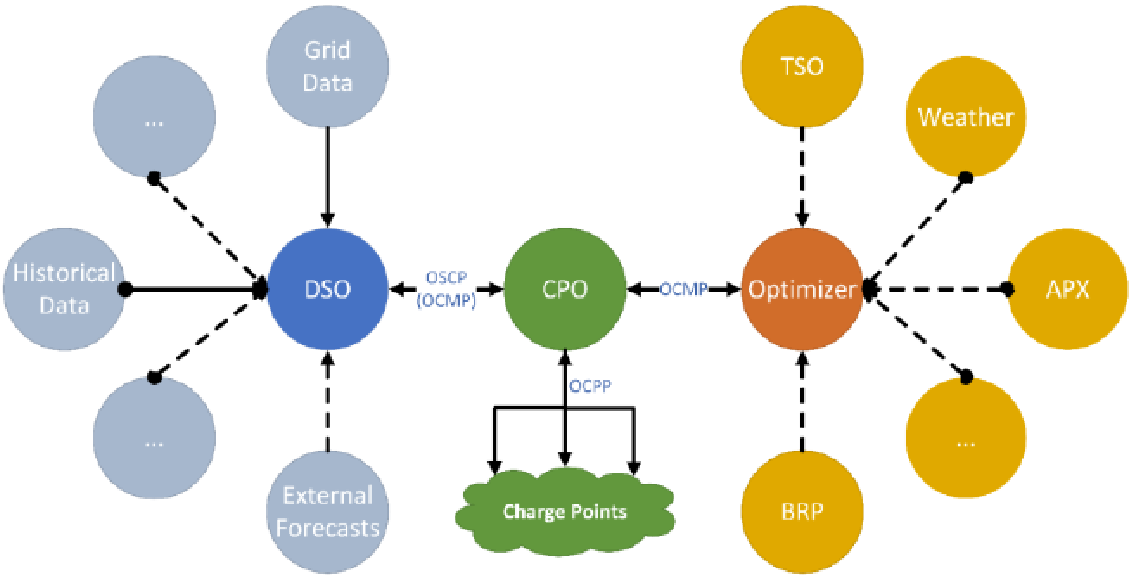
For both groups of chargers (i.e. neighborhoods) we specified capacity limits based on the maximum available capacity on the transformer in that neighborhood. We would have wanted to use live measurements for this, but in absence of such measurements we calculated the available capacity. We multiplied the number of households connected to the transformer with historical usage profiles for energy consumption, available at 15 minutes intervals. The total amount of energy consumed determines the non-flexible load profile for the transformer. The transformer load for any neighborhood is highest in the early evening in winter. Differences in the number of households connected have resulted in unique capacity profiles for both neighborhoods.

Adding to existing open communication standards

In our pilot project we worked with open standard communication protocols. Specifically OCPP (the Open Charge Point Protocol) and OSCP (Open Smart Charging Protocol). In order to send and receive profiles to and from the aggregator and run our Smart Charging algorithm, we developed additions to OSCP, named OCMP during the project. These additions will be released as part of the new version of OSCP: OSCP 2.0. So everyone can use and benefit from this additions.

We created a system in which the different stakeholders are connected using the open protocols:

a. DSO (Distribution System Operator): prediction of electricity grid usage - on district level
b. CPO (Charge Point Operator): controlling charge transactions – on grid connection level
c. Optimizer: INVADE platform energy management - on district level

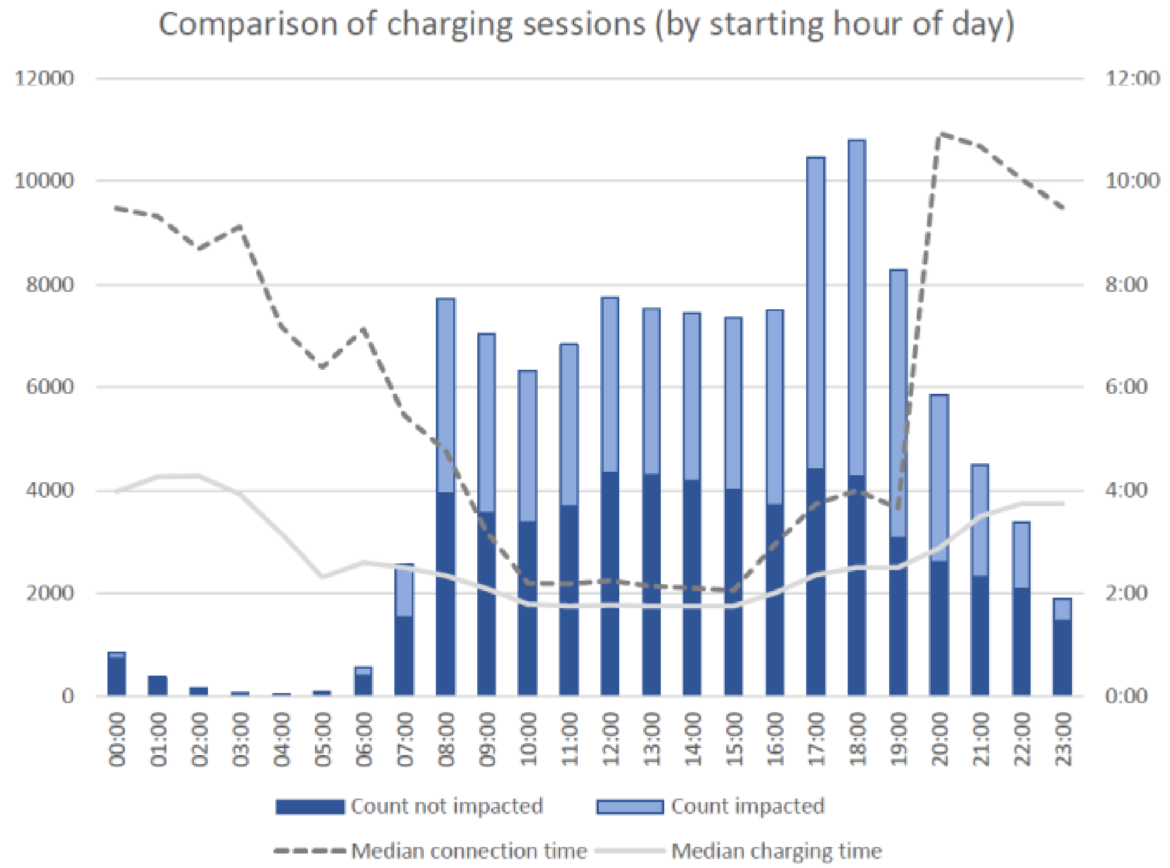


While developing the additional requirements in the protocols, the response times of the feedback loops between DSO and CPO and between Optimizer and CPO were essential. Because new sessions can be added at every moment in time, the system has to have rules to prioritize incoming triggers. In our case, DSO triggers always overruled Optimizer triggers. Some more server capacity to ensure system performance is likely to be needed if the system is scaled up to numbers significantly higher than our pilot group of 1,000 charge points, but for the current system we encountered no problems.

Managing 15.000 sessions per month in real time

After designing the set up and developing the software adding to open communication standards we could start with the actual large scale Smart Charging test. Since we used existing chargers, we had no delay in finding users for our chargers and could start Smart Charging immediately. Our Smart Charging algorithms controlled the speed of charging for 160,000 charging sessions between January 2019 and November 2019, that is more than 15.000 per month! In half of the sessions the speed of charging was adjusted to values below 20 Amperes to prevent a virtual overload of the network. These sessions were counted as “impacted” in our evaluation. The adjustments occurred mostly at the evening peak hours and showed clear seasonal differences.

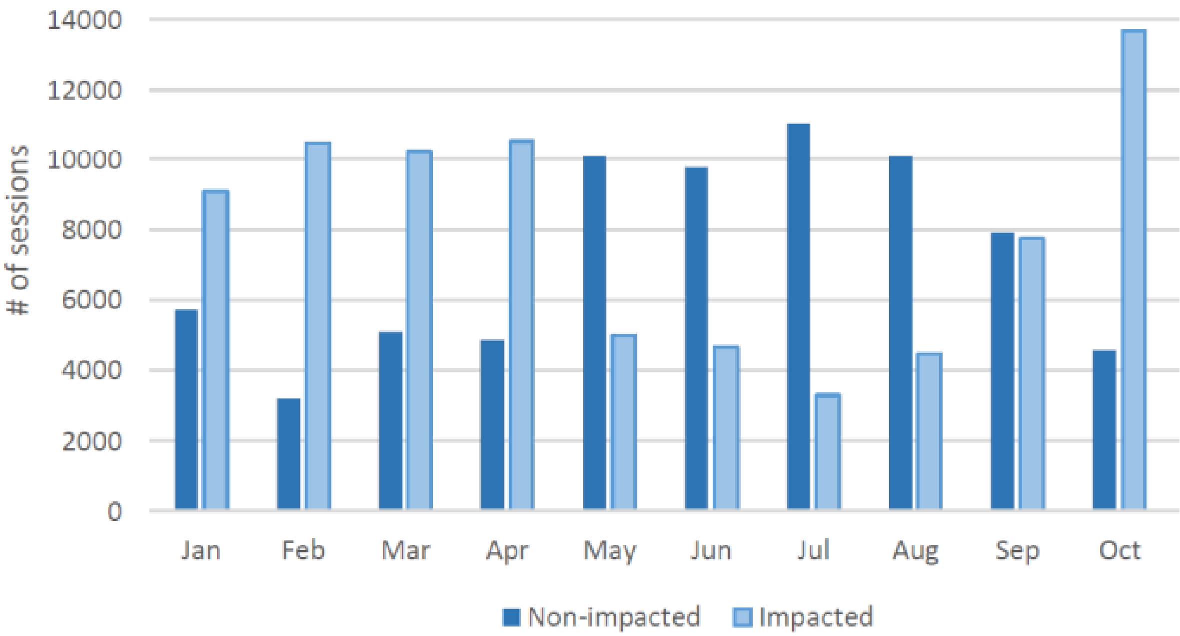
The effect of the Smart Charging algorithm on the charging sessions. When the requested load capacity threatened to go over the available capacity (red line in the middle figure), the Ampèrage of all running sessions was adjusted downwards, but never below 13 Amperes (bottom figure).



Number of sessions (left y-axis) and session duration (right y-axis) per starting hour. Comparison between sessions where adjustments were made and where this was not necessary. More adjustments are made in the evenings, but because the connection time is also very long during that period there was enough time in the sessions to compensate for the lower charging speed.

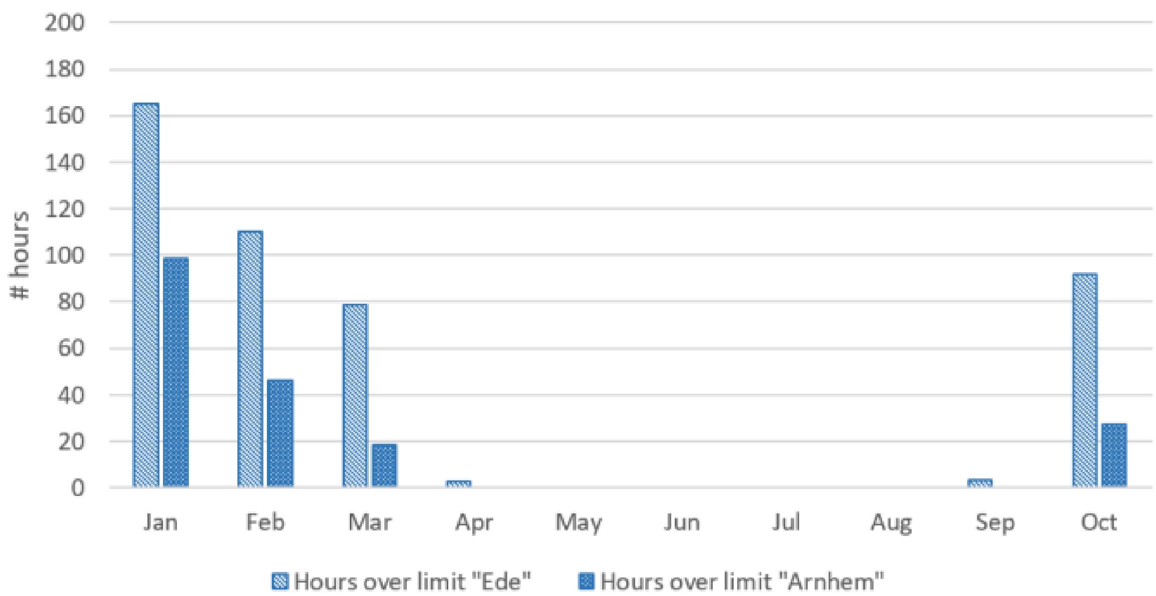
Seasonal effects: summer vs winter

Smart Charging adjustments showed clear seasonal influences. Significant intervention was more often required in winter. This is because then there is more power demand, for example from heat pumps but also for the electric cars themselves. So DSO limits were lower in winter. Which is why in winter a larger share of charging sessions was impacted compared to the summer period. To be more specific: in February, 77% of charging sessions were affected by the control algorithm, compared to 23% in July.

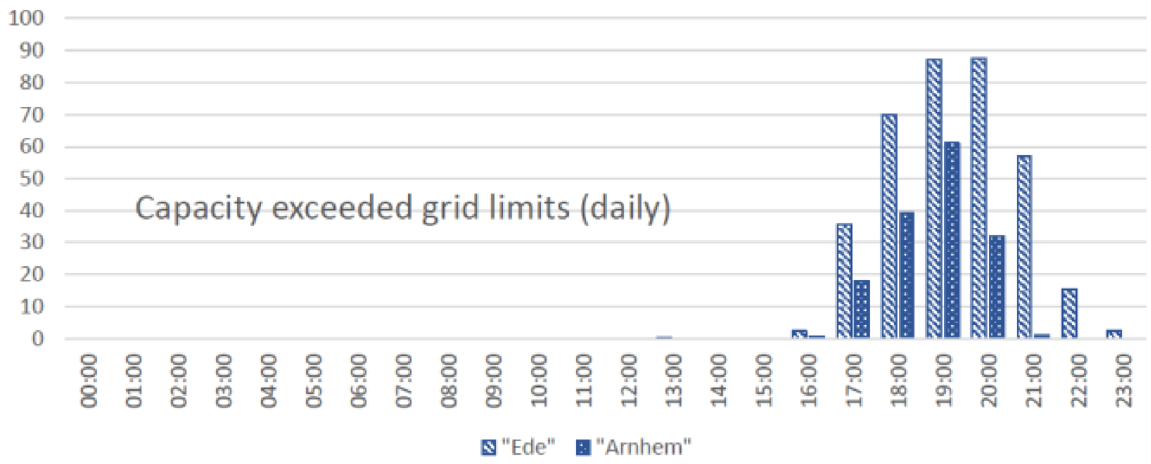


Impacted and non-impacted sessions per month. In winter there are more impacted sessions than non-impacted. In summer it's the other way around: more non-impacted sessions than impacted.

Moreover, in the winter months, the limit of 13 Amps (lowest charging speed allowed during the experiment) was not sufficient to remain below the maximum (virtual) network load.



Overview of the number of hours per month where the chosen lower limit of 13A for the charging speed was not low enough to stay within the capacity limits, and the charging sessions therefore fictitiously caused the network to be overloaded. A clear seasonal effect is visible.



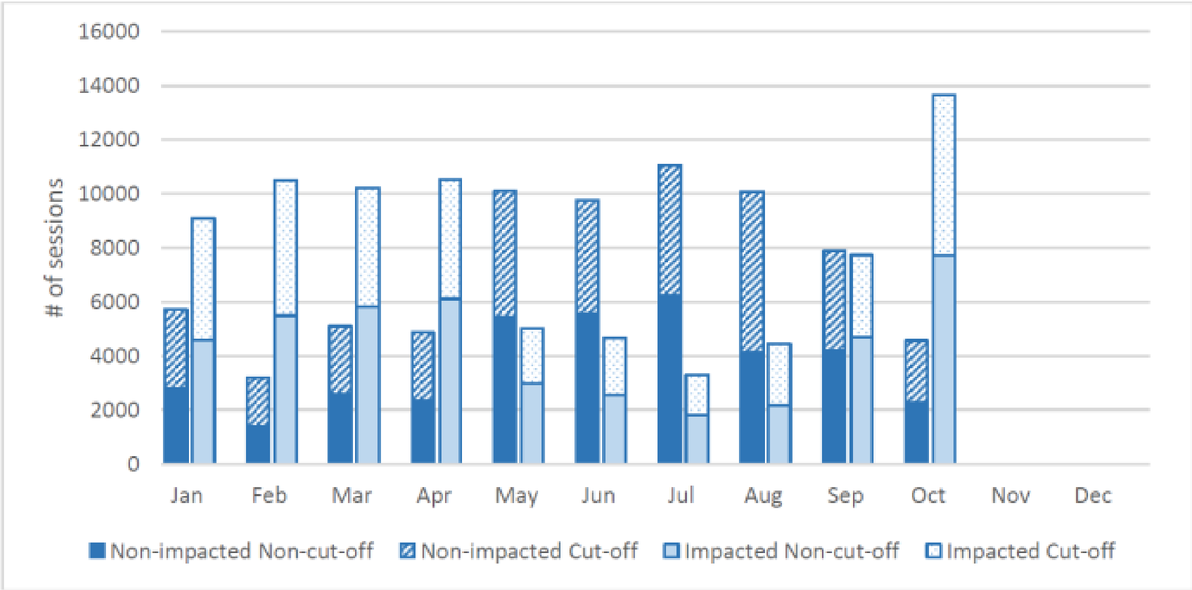
Daily pattern of the moments when capacity exceeded grid limits, so the limit of 13 Amperes we set was not low enough to keep the charging within grid capacity limits. This occurred in wintertime during the evening peak hours both in Arnhem and Ede.

How to determine impact for the EV driver?

One of our aims for the pilot was to avoid any disturbance in the charging experience of drivers. This was important, as we carried out the experiments on public charge points that were already in use. So, did we succeed in this?

First, a lower boundary was needed to avoid charging sessions losing connection with the charge point operator. Not having a lower boundary could result in some electric cars going into irreversible 'sleep' mode when charged at too low charging speed. In the setup we chose to never allow charging below 13 Ampere to avoid unsatisfactory charging sessions. This is higher than the lowest boundary needed to avoid losing connection. We estimated it was a safe boundary to allow enough charging on the connections to avoid dissatisfied customers, as it can also occur on regular charger with a 3*25A connection when two cars charge simultaneously.

Because our lower boundary is however significantly lower than the maximum output of the charger, we looked into the sessions to determine the impact of our algorithms on charging with respect to the amount of energy charged. In theory, the reduced charging rate can lead to more EVs being cut off before they are fully charged, compared to the situation without Smart Charging. In a cut off, the charging session is not finished when the connection to the charging station is ended. A cut off in a session that took place at reduced charging speed is likely to have charged less kWh.

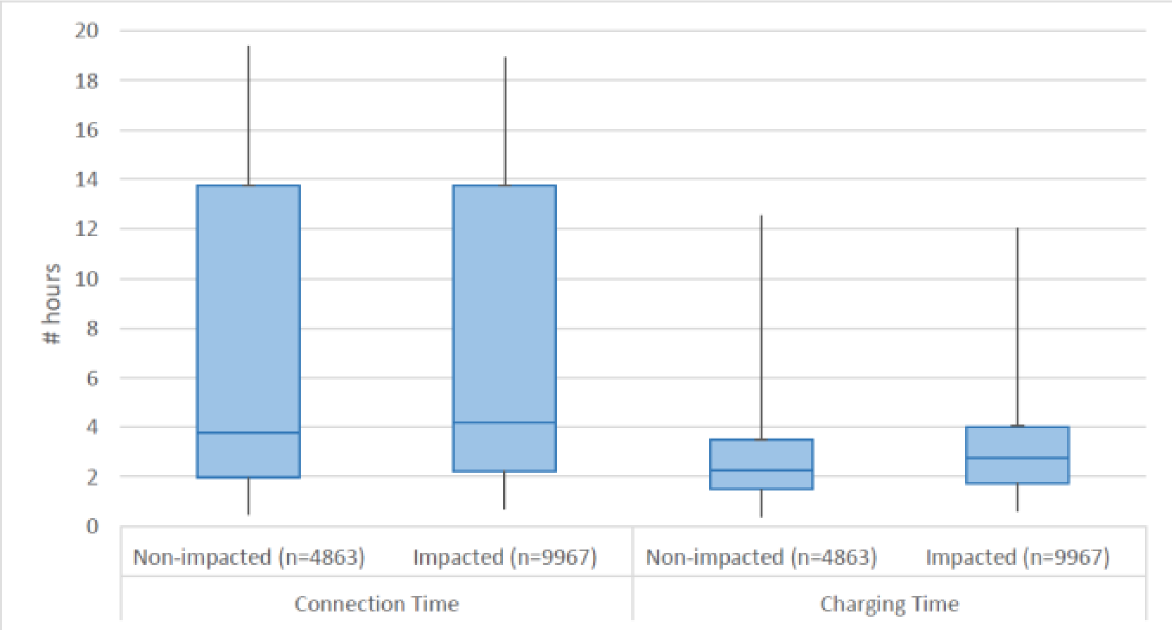


Comparison of cut-offs in the two groups of sessions, non-impacted and impacted. Both groups have cut-off sessions. The non-impacted sessions have slightly more cut-offs than the sessions that were impacted by our Smart Charging algorithm.

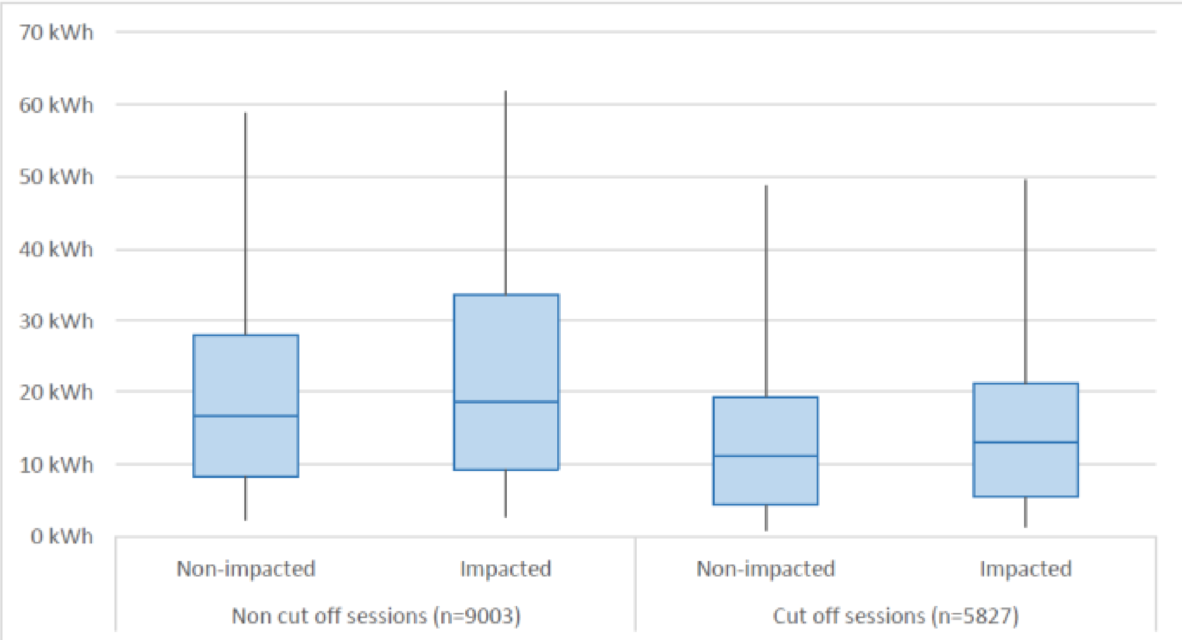
Early evening

Contrary to our expectations, the impacted sessions were cut off slightly less than the sessions that were not impacted: 44% vs 49%. One explanation for this observation is that the connection times of the sessions that were impacted were longer on average. An analysis of the distribution of charging start times throughout the day, compared to the total connection time of each session confirms this.

To check if the sessions did not experience any negative effects of our Smart Charging algorithms only because they are connected long enough, we looked into the specifics of the sessions that started in the early evening. When looking into the connection duration compared to the charging duration the average connection time of both impacted and non-impacted sessions is almost similar. The charging time ofcourse differs. Based on the overlap in the averages for connection and charging time, there appears to be a group of early evening sessions that leaves relatively soon and is likely to experience a cut-off during the session. To explore this some more we analysed what percentage of early evening sessions is a cut-off and how much energy these sessions received.



Connection times versus charging times for all sessions started in the early evening (18:00-19:00h). Horizontal lines in the box plots are the averages, column shows the first standard deviation.



Cut-off sessions within the group of sessions that started in the early evening (18:00-19:00h) Amount of energy charged in the cut-off sessions, meaning the sessions in which connection time equals charging time.

Interestingly, the amount of energy charged in the cut-off sessions that were impacted by our Smart Charging algorithm is slightly higher than in the non-impacted cut-off sessions. The most likely explanation is that the sessions were not similar with respect to starting conditions and parking time, with the cut-off impacted sessions having more favorable conditions for the amount of energy they could charge than the non-impacted cut-offs. That we found this result with this large number of sessions (almost 15.000 sessions within this timeframe) was not expected. It indicates that Smart Charging does not necessarily cause different charging outcomes with respect to delivered energy, even in cut-off sessions. We expected our set-up, that treated all cars as equals, to cause differences with respect to the amount of delivered energy in impacted cut-off sessions compared to non-impacted cut-off sessions. By chance, this did not happen. In an ideal situation we would want to know how much energy each car needs, to prioritize charging speeds in the group of sessions. However, within the current set up, we could not divide sessions into groups with special Smart Charging strategies in order to distribute the energy among electric cars differently. Not much user interaction is needed to improve the algorithm: transmission of the state of charge of each car would already allow more tailor-made Smart Charging.

It's also good to mention that as far as we know CPO EVnetNL did receive only one complaint about the lower charging speed during impacted hours. One driver asked why the charging station was not operating at its normal charging speed and requested it to be put back to business as usual.

Overall conclusions

After having run the Smart Charging algorithm on a large scale during several months, what conclusions can we draw from the experiment?

- Large-scale control of the speed of the charging of electric cars using a Smart Charging algorithm on public charging stations works. We have developed a Smart Charging system that can control large number of charging sessions to respond to real time grid limitations. Using standard controls, operated for all active sessions simultaneously, we have monitored over 160.000 sessions and have successfully sent out adjusted charging profiles to 52% of these sessions, limiting charging to below 20A (but not lower than 13A). We have not found a significant effect on kWh charged between sessions that were and were not impacted. Our protocol (within the limitations we used) allows the efficient charging of large numbers of EVs within the capacity restrictions of the transformer in the neighborhood the charging stations are (virtually) connected to. This was done without any significant difference in charged energy between groups of EVs that did and did not have Smart Charging adjustments applied to their session.

- Due to the low degree of adjustment (not below 13 Amps) and the coherence between large connection times and most impacted sessions (due to peak energy demand) both occurring in the early evening, the effect of our Smart Charging algorithm was hardly noticeable for the driver. The median connection time roughly equals the median charging time between 10AM and 4 PM for all sessions. An average session is about 2 hours. At other times of the day, the connection time is always (much) higher than the charging time. Impact can be further reduced using more advanced optimization algorithms if data about driver mobility need (travel plan, battery information) is available.

- Smart Charging adjustments took place in half of the sessions and showed clear seasonal influences. Interventions were more often required in the winter. This is because then there is more power demand, for example from heat pumps but also for the electric cars themselves. As a result, you will reach the maximum load of the local power grid and the transformer faster and you will need to adjust the charging. Moreover, in the winter months, the lower limit of 13 Amps used during the experiment was not sufficient to remain below the maximum (virtual) network load. Seasonal influences will therefore have to play a role in Smart Charging strategies.

- Smart Charging of a group of charge stations is more effective compared to individual charging stations. The available grid capacity can be optimized better between active sessions.

Next steps…

The end of a successful project like the large scale Smart Charging pilot we did in INVADE, is only a start for the further exploration and spreading of the concept. So what are some next steps to be taken in the development of Smart Charging?

- Since our pilot results are positive, we will further develop our protocol adaptions to a new release of OSCP (OSCP 2.0) so everyone can use them and further build on them.

- Further improvements to the Smart Charging algorithm can be made as soon as car manufacturers share information about the car battery, such as State of Charge and total battery capacity. If we could obtain more information per charging session to use as input for the charging, this could be used to further optimize Smart Charging in connected groups of chargers by taking into account the expected energy needs per EV. We therefore invite car manufacturers to supply these data through the open protocol already in place between vehicle and charger, so that other parties can use it.

- The open protocols we used offer possibilities to add extra decision rules, for instance based on price or capture of durable energy. This could optimize Smart Charging possibilities further.

- Further research is to be done with a lower charging limit in the Smart Charging algorithms (even delaying the charging altogether at certain times) and the effect on the EV's. Some models could ‘go to sleep’ with negative effects on the driving experience. How can we solve this?

- More research and pilots on similar Smart Charging strategies for charging at home (private) and at work (semi-private) should be done, building also on the experiences of the other Dutch pilot as done by GreenFlux (see below).

- Seasonal effects should be included in Smart Charging strategies.

- In due time also the possibilities of Vehicle to Grid (V2G) should be tested in a large scale pilot.

The other Dutch Smart Charging pilots

V2G demonstration at the ElaadNL site in Arnhem during an INVADE meeting - Foto: Nynke Arends

The large scale Smart Charging project we did was one of the Dutch pilots as part of the European Horizon 2020 subsidized INVADE project. As Dutch pilot owners, together with GreenFlux and in corporation with EVnetNL, we explored the possibilities of matching energy demand to sustainable energy generation, grid capacity and improved Smart Charging of electric vehicles.

As we focused on the large scale Smart Charging test by ElaadNL in this paper, here is some information about the other parts of the Dutch INVADE pilot: GreenFlux focused on Smart Charging in people's homes and offices. The company provided the test with 40 households and 8 office locations (with no fewer than 199 semi-public charging points). In the home situation, the cars were charged as much as possible with locally available sustainable energy generated from solar panels, while users had the option of overruling the Smart Charging profile. This was also done at the office locations with wind energy as a steering factor. As a result, experience has been gained regarding the prevention of overloading the power grid. Find out more about this part of INVADE on the website of GreenFlux: https://www.greenflux.com

And the other participation of ElaadNL in the pilot was about testing vehicle to grid opportunities. Read more about the surprising results in the article we wrote on our website: 'Testing Vehicle to grid (V2G) possibilities in the INVADE project, with surprising results' https://www.elaad.nl/news/testing-vehicle-to-grid-v2g-possibilities-in-the-invade-project-with-surprising-results/.

The European INVADE H2020 project

INVADE is a European subsidized project from the Horizon 2020 Research and Innovation program. The abbreviation INVADE is derived from the objective for the integration of electric vehicles and batteries in the distribution network for accessing distributed and centralized energy storage.

The idea: renewable energies and EVs change the way we consume and produce electricity. It also changes the way those who manage and distribute it must think about the electricity system – to always provide the best possible service for the connected costumers. But these things are difficult, and often take a long time. The goal of the EU funded Horizon 2020 project INVADE is to greatly speed up this process, by showing that the technologies and solutions we have today, only must be connected in new ways to solve the challenges of tomorrow.

The INVADE project started on January 1, 2017 and runs until the end of 2019. In the project, 12 partners work together at 5 test locations (the Netherlands, Norway, Germany, Spain and Bulgaria). Extensive information about the INVADE project can be found at: https://h2020invade.eu/

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 731148.