The impact of Electric Vehicle charging on grid short term frequency and voltage stability, and cascade fault prevention and recovery.

Work Package 1 report prepared by Sygensys for National Grid ESO

February 2022

Resilient Electrical Vehicle Charging: “REV”

SYGENSYS

EXECUTIVE SUMMARY

New Smart Loads = New Risks

Decarbonization of the economy will drive a transformation of the GB power system beyond that already caused by the growth in renewable energy.

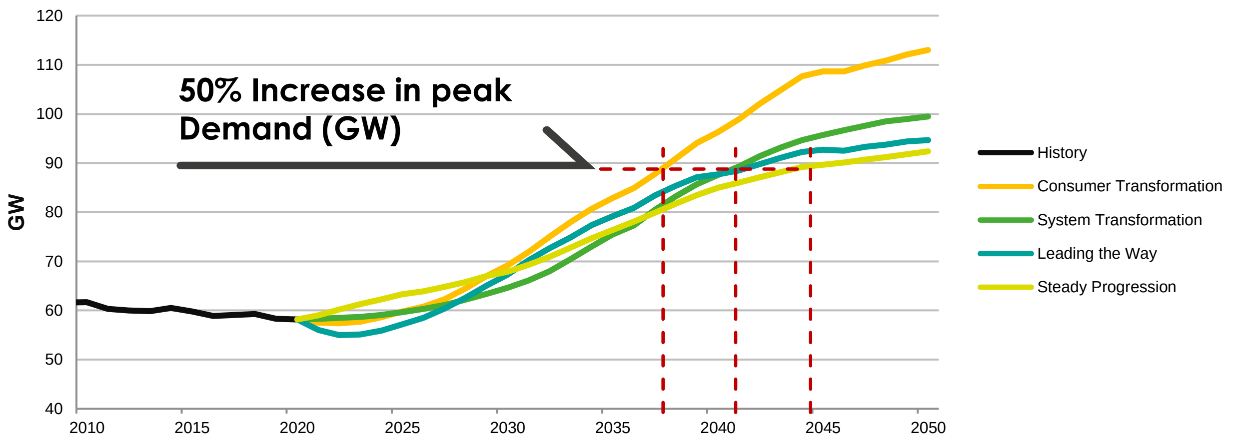
By around 2040

- peak demand is forecast to increase by 50% in all Future Energy Scenarios (FES[1]),
- demand for energy will at least double over the same time period in three out of four scenarios.

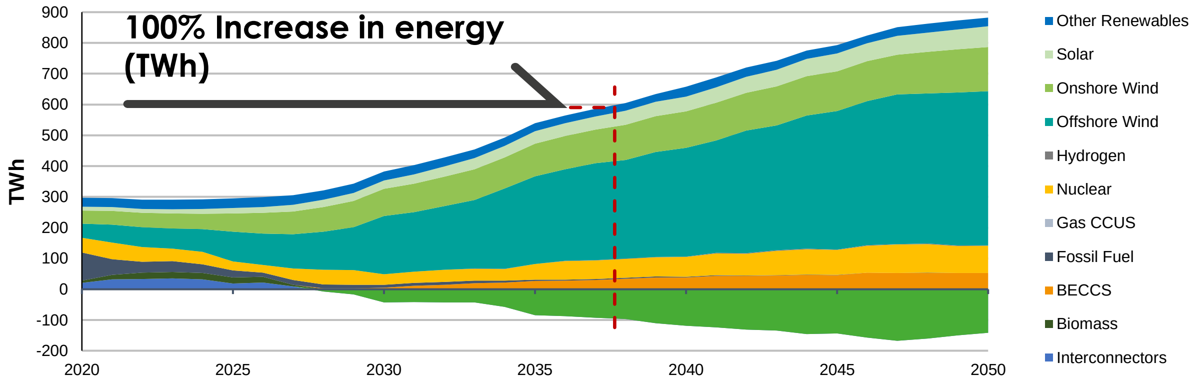
Much of this new demand will come from "smart" loads, controlled by software systems, whose behaviour will be very different to traditional system demand. **Just as inverter-connected generation has brought new challenges for grid operation, the presence of these new types of smart load will introduce system risks that have not been seen before.**

Phase 1 of Project REV[2] has explored what these risks might be for one rapidly growing group of technologies, Electric Vehicle Charging (EVC) and Vehicle-to-Grid generation (V2G).

1) Future Energy Scenarios, July 2021, National Grid ESO
2) Project REV NIA2_NGESO006



Future Energy Scenarios, July 2021, National Grid ESO



Future Energy Scenarios, July 2021, National Grid ESO
Consumer transformation

We need to prepare now for the increase in demand in the 2030s from the forecast mass adoption of EVs and other low carbon technologies.

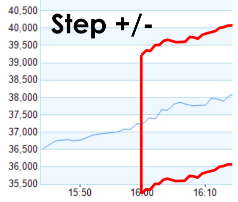
SYGENSYS

EXECUTIVE SUMMARY

Six ways in which Electric Vehicle chargers present a risk to grid security

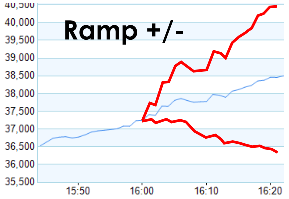
1. Step: Too many chargers switching on or off at the same moment

- Time of use tariff step (real or accidental)
- Failure of fault ride-through
- Software error (EV vendor, DSR aggregator, etc)
- Malicious actors



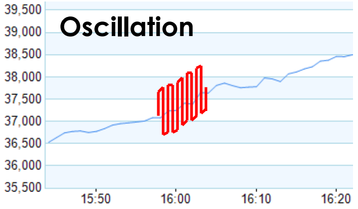
2. Ramp: Too many chargers switching on or off within a few minutes

- Software-controlled load pick-up
- Cascade tripping for high or low volts
- “Panic charging”

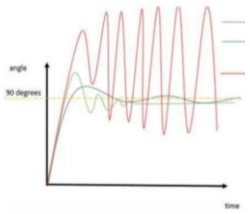


3. Oscillations: A group of chargers switching on and off repeatedly

- Control system interactions
- Malicious actors

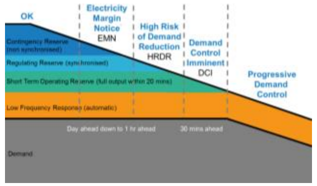


POWER OUTAGE



4. Degraded stability: Increases risk of post-fault collapse

- Constant Power loads will impact voltage, transient and oscillatory stability of the system.
- V2G lacks inertia and PSS.



5. Demand control: Defences are eroded

- Constant Power loads will not respond to voltage reduction.
- V2G will offset LFDD operation.

6. Restoration: Erratic behaviour after restart will hinder the process of restoration

- Load return depends on restart of hardware, software and communication systems.
- Risk of tripping on high or low volts during restoration.
- Risk of transformer overloads

Mass adoption of EVs will bring a range of new system operability challenges for grid operators, not just the increase in energy demand.

EXECUTIVE SUMMARY

Underlying factors

Common-mode behaviour reducing load diversity.

The 2021 Future Energy Scenarios[1] envisage between 12 and 26 million EVs in service in 2035. With typical 7kW domestic chargers, just 2% of these chargers switching on at the same time would generate a load step of between 1.7 and 3.6 GW, significantly more severe than the August 2019 loss of supply incident[2].

Smart charging control systems could cause such synchronised action by responding to Time-of-Use tariffs, by accident or through malicious intent.

Randomisation helps soften load steps, but the volume of price-driven demand could still result in rapid multi-GW ramps.

Design for customer needs, not grid requirements.

The focus of EVC/V2G technology design is customer needs and cost; it will do "just enough" to meet grid-related regulations such as fault ride-through and high/low voltage withstand. Present regulations were not designed for a zero-carbon future so will need revision.

Charging speed is maximised by constant power / current operation, with no load response to voltage or frequency excursions. This will negatively impact system stability.

1) NGESO Future Energy Scenarios July 2021
2) 9 August 2019 power outage report - Ofgem
3) Accelerated Loss of Mains Change Program

Dependence on an interconnected software ecosystem.

Smart charging depends on multiple software systems running on multiple hardware platforms from multiple vendors connected by multiple communication systems.

This complexity creates the risk of conflicting controls and unforeseen behaviour under normal and abnormal conditions (loss of comms or restoration after loss of power), and a high risk of cyber compromise.

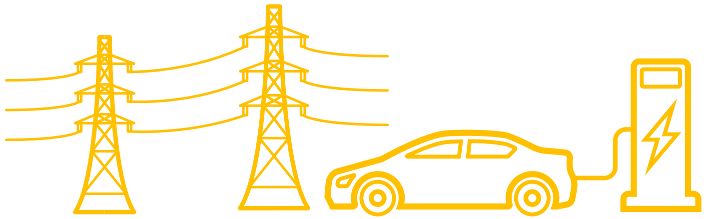
An urgent decarbonization agenda.

It is vital that regulations are updated quickly to manage these risks while giving the industry time for implementation so that we avoid the need for a significant retrospective program (such as ALoMCP[3]);

NGESO should consider whether ToU tariffs, in the present half-hour market, will be viable when up to half of system demand is price-responsive.

Exploiting the full capability of smart EV charging Demand Side Response (DSR) flexibility and V2G can support decarbonization targets, reducing operating costs and enhancing system resilience.

Urgent action is needed on regulation, system and market design to successfully mitigate risk from EVC and V2G, and unlock their benefits.



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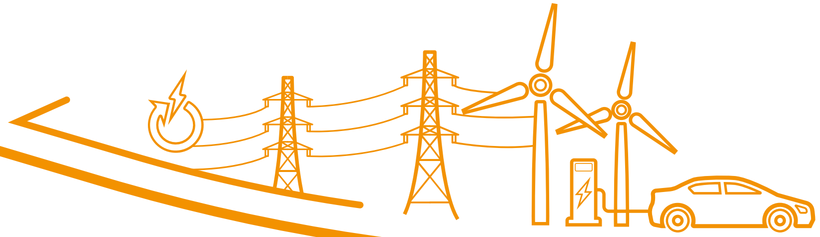
CHAPTER 2

Abbreviations

AC	Alternating Current
ADMD	After Diversity Maximum Demand
AEMO	Australian Energy Market Operator
ALoMCP	Accelerated Loss of Mains Change Program
ANM	Active Network Management
BAU	Business As Usual
BEIS	Dept for Business, Energy & Industrial Strategy
BEMS	Building Energy Management System
BESS	Battery Energy Storage System
BMS	Battery Management System
BS	Black Start
BSI	British Standards Institute
CCS	Combined Charging System
CVR	Conservation Voltage Reduction
CP	Charge Point
DER	Distributed Energy Resource
DC	Direct Current
DCC	Data Communications Company
DDoS	Distributed Denial of Service
DG	Distributed Generation
DPV	Distributed Photo Voltaic
DSR	Demand Side response
DN	Distribution Network
DNO	Distribution Network Operator
DSO	Distribution System Operator
ENA	Energy Networks Association
EPRI	Electric Power Research Institute
ESA	Energy Smart Appliance
ESC	Energy Systems Catapult
ESIG	Energy Systems Integration Group
EV	Electric Vehicle
EVC	Electric Vehicle Charging
EVSE	Electric Vehicle Service Equipment
FES	NGESO Future Energy Scenarios
FIDVR	Fault Induced Delayed Voltage Recovery
FiT	Feed in Tarif
FRT	Fault Ride-Through
GB	Great Britain
GFM	Grid ForMing
GIC	Geomagnetic Induced Current
G-PST	Global Power Systems Transformation Consortium
HEMP	High Energy Magnetic Pulse
HEMS	Home Energy Management System
HGV	Heavy Goods Vehicle
HP	Heat Pump
HV	132 kV and above
HVDC	High Voltage Direct Current
IBR	Inverter Based Resource
IC	Inter Connector
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IET	Institute of Engineering Technolgy
ISO	International Organization for Standardization
ISP	Internet Service Provider
kW	kilo Watt
kWh	kilo Watt hour
LCT	Low Carbon Technology
LFDD	Low Frequency Demand Disconnection
LV	240V single phase to 11kV three-phase
MV	33-132 kV
MW	Mega Watt
NEM	National Electricity Market (Australia)
NERC	North American Electric Reliability Council
NPL	National Physical Laboratory
NGESO	National Grid Electricity System Operator
OBCM	On Board Charger Module
OEM	Original Equipment Manufacturer
OFGEM	Office of Gas and Electricity Markets
OVLO	Over-Voltage Lock Out
PAS	Publicly Available Standard
PLL	Phase Locked Loop
PU	Per Unit
PV	Photo Voltaic
REV	Resilient EV charging project
RIIO	Revenue = Incentives + Innovation + Outputs
RoCoF	Rate of Change of Frequency
SCL	Short Circuit Level
SPEN	SP Energy Networks
SSO	Sub Synchronous Oscillation
SSTI	Sun Synchronous Torsional Interaction
ToU	Time of Use
TSO	Transmission System Operator
TN	Transmission Network
TWh	Tera Watt hour
UKPN	UK Power Networks
UL	Underwriters Laboratories
UPS	Uninterpretable Power Supply
UVLO	Under-Voltage Lock Out
V2G	Vehicle to Grid
V2X	Vehicle to X (X = Building, Home, Load, Grid)
VPP	Virtual Power Plant
VS	Vector shift
WAN	Wide Area Network
WPD	Western Power Distribution



CHAPTER 3

Introduction

This section introduces Sygensys and Project REV.

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SYGENSYS

Company Overview

Sygensys is a start-up developing demand management and energy storage system solutions to allow effective use of renewable energy sources. Our vision is to leverage the incredible potential of bi-directional power flow from electric vehicles and battery energy storage systems to help balance electricity supply and demand, both on public grids and local microgrids.

Our solutions will provide a secure supply to domestic and industrial consumers even when electricity systems are hit by storm damage, equipment failure or cyber-attack.

Sygensys is developing patented technology to enhance the performance of Electric Vehicle (EV) charging and Vehicle to Grid (V2G) technology improving grid resilience. We are working with a wide range of collaborators including grid operators, regulators, end users and semiconductor vendors to bring these innovative solutions to market.

Through Project REV, and other collaborative R&D activity, we will enable resilient demand side response, to provide reliable stability services which grid operators can depend on to balance the 100% renewable energy Green-Age Grid[1].

1) Power Converters: A Growing Challenge to Grid Stability?

FOREWORD

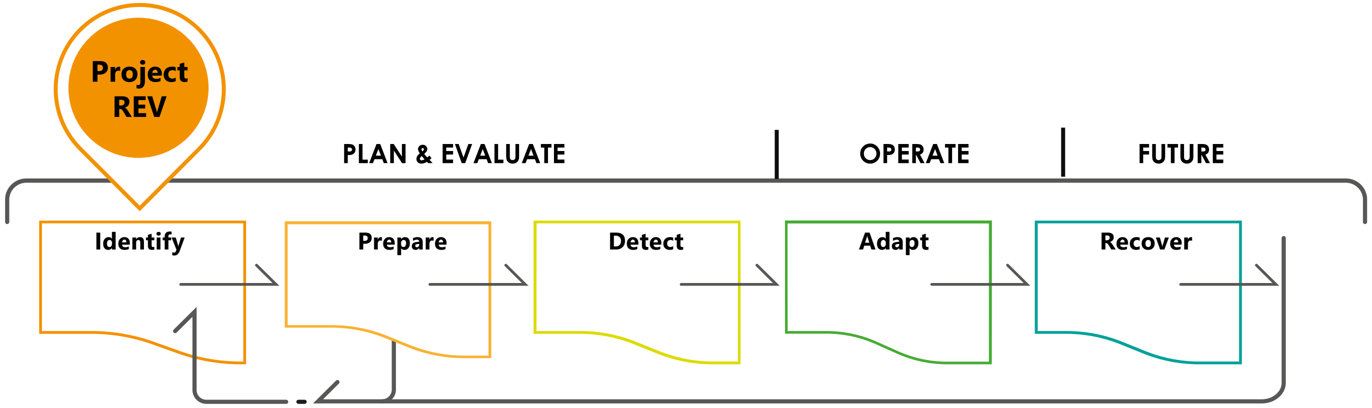
Introduction to Project REV

Project Resilient Electric Vehicle Charging (REV) is analysing the potential future impact of Electric Vehicle (EV) charging on electricity grid short term (1 cycle to 10 seconds) frequency and voltage stability, and cascade fault prevention and recovery.

This mid-project WP1 report aims to identify, and raise awareness of, the emerging risks as electrification of transport increases. An individual charger, typically 7kW, has a relatively small impact on the grid. The analysis focuses on events which would cause a change in multiple chargers at the same time and/or in a local area and the impact on electricity system operations.

This project does not concentrate on the benefits of time-shifting of demand, which has been investigated in a number of previous studies. However, it does investigate the impact of these and other control systems on short-term grid stability.

We need to prepare now for the mass adoption of EVs by the 2030s. Further analysis, improved system design and regulatory enhancements are all required for continued smooth and efficient running of the electricity supply system.



Core Functions of Resilience

Resilience Framework for electricity energy delivery systems, INL

Project REV concentrates on the Identify phase of the grid resilience management process.

Project REV

Analysis Process

A key objective of Project REV is to identify the mechanisms which may impact short term grid stability and recovery from incidents. This has been undertaken through a series of brainstorming sessions with input from industry sector experts from organizations including:-

- Sygensys – Project lead
- National Grid ESO (NGESO)
- Energy System Catapult (ESC)
- UK Power Networks (UKPN)
- Electric Power Research Institute (EPRI)
- National Physical Laboratory (NPL)

We thank all contributors for sharing their knowledge.

This report has been produced by Sygensys based on the input of the brainstorming participants, but it may not reflect the views of those organizations or the individual participants. It is a mid-project report and final conclusions may be different to the initial findings presented here.

We would welcome feedback from NGESO on the preliminary findings in this report, as well as from participants in the EV charging supply chain including vehicle and charge point designers and manufacturers, operators, aggregators and DNOs.

CHAPTER 4

The new world of EV charging technologies

This section provides an introductory briefing that sets the context for the findings of Project REV. Many readers will be familiar with some, but probably not all, topics. We hope a scan read at least should find some new and interesting content for all readers.

CHAPTER CONTENTS

DEMAND GROWTH

Balancing supply and demand after a fault

Electricity supply from generators and demand by consumers must always be closely balanced. This is essential to maintain the supply frequency to consumers within regulatory limits.

As demand from consumers varies, the output from generators varies to match, keeping the system in balance. If there is sudden disruption to that balance, for example the failure of a generator or HVDC interconnector, balance must be restored quickly.

Response that is too slow, or incorrect, could lead to wide deviations in frequency and ultimately loss of supply for consumers.

Reliable, cost-effective solutions should be employed to maintain grid balance. The whole system must be designed to be resilient, for example ensuring that generators can ride though faults to maintain supply to consumers.

We can't simply build enough infrastructure and hold enough reserve capacity to respond to all possible events. Regulations[1] therefore set out a reasonable list of severe events ("contingencies") for which the lights must stay on.

The case study, right, is based on the most significant GB incident of this type in recent years.

1) Security and Quality of Supply Standard

This unexpected loss of generation meant the frequency fell and went outside the normal range of 50.5Hz – 49.5Hz.

The National Grid Electricity System Operator (ESO) balances supply and demand second by second to maintain the frequency of the system at 50Hz.

In case of an event of large frequency change, the ESO keeps backup power, designed to cover the loss of the single biggest generator to the grid. At this time, the ESO was keeping 1,000MW of backup power.

All the normal backup power and tools were used. In this case it included 475MW of battery storage.

The sequence of events of Friday 9th August 2019

Friday 9 August 2019

"A power outage caused interruptions to over 1 million consumers' electricity supply. Several other services were disrupted due to the affected service providers' own safety systems or problems with their back-up power supplies. The rail services were particularly affected with more than 500 services disrupted.

The security and reliability of energy supply is a key consumer outcome for the sector, a principal objective for Ofgem as the energy regulator, and an important **consideration for the future in an evolving electricity system.**"

9 August 2019 power outage report - Ofgem

The security and reliability of energy supply has to be balanced against the cost of infrastructure and generation reserve capacity.

DEMAND GROWTH

How will EV charging change grid behaviour?

EV charging is a major new type of load on the grid. It uses AC to DC power converter technology. We can learn from the issues experienced with power converter connected generation and pre-emptively address potential issues which may occur as a result of mass adoption of EV charging.

When converter-connected resources were initially used for electricity generation, they were considered small-scale, providing little power, so little if any risk to grid short-term stability. As the power provided by these resources has increased, their impact on grid stability has increased. For example, they were a contributory factor in the August 2019 incident, and they remain a major concern (as evidenced, for example, in the ALoMCP[1] programme).

Although EV charging and V2G is at a small scale currently, based on the previous experience and forecast growth, we should anticipate a range of challenges which may include:-

- Changing grid transient behaviour
- New types of failure mode
- Modelling and analysis challenges
- The need for updates to related regulations
- Difficulty deploying remedial updates to installed devices

All these challenges will need addressing in the years ahead.

1). ALoMCP programme

"Even with a requirement to maintain an EV charger in operation for some dip conditions, few works in the literature cover the impact of voltage dips in the type of equipment. The impact of the tripping of EV chargers in the grid is discussed in [19]. The main conclusion of [19] is that **the tripping of EV chargers could result in the loss of a significant proportion of the total load**, which could lead to unacceptable high voltages in the distribution feeders."

Impact of Electric Vehicle Charging on The Power Grid
[19] S. Kundu and I. A. Hiskens, "Overvoltages due to synchronous tripping of plug-in electric vehicle chargers following voltage dips," IEEE Transaction on Power Delivery, vol. 29, no. 3, pp. 1147-1156, June 2014.

New load types will impact grid stability; now is the time to act, rather than waiting until we have a large installed base of EV chargers and V2G.

DEMAND GROWTH
Decarbonization of Transport

“The UK has committed to Net-Zero carbon emissions by 2050. Transport is currently the largest emitting sector of the UK economy, responsible for 27% of total UK greenhouse gas emissions. Over half the UK’s transport emissions (55%) come from cars.”[1]

In 2020 the government announced a historic step towards net-zero with ending the sale of new petrol and diesel cars by 2030. Then in 2021 they have confirmed a pledge for zero emissions HGVs by 2040. This will further accelerate the adoption of electric vehicles.

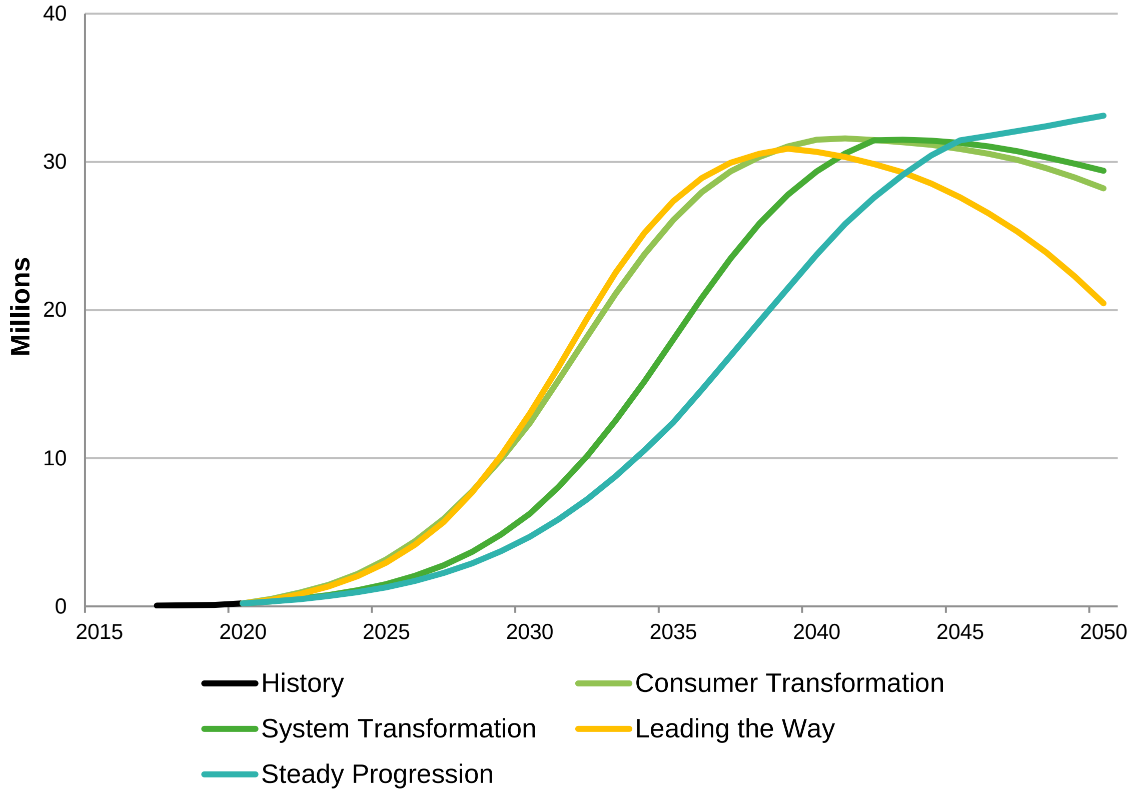
To support increasing transport electrification, the government will mandate electric vehicle charging for new building developments.

The Future Energy Scenarios report[2] published by National Grid ESO in 2021 indicates that there could be over 30 million electric cars on the road in the late 2030s. Demand from vans, buses and a wide range of other electric vehicles will be additional to this.

1). Electric vehicles and infrastructure, December 2021, House of Commons Library
2). Future Energy Scenarios

Number of Battery Electric Cars on the road

Future Energy Scenarios, July 2021, National Grid ESO



With new laws and changing attitudes across society, mass adoption of EVs is coming... the only question is when... soon or very soon?

SYGENSYS

DEMAND GROWTH

Meeting new demand

As we decarbonize the economy, other loads, alongside EV charging, will also increase significantly. For example, the government is promoting the decarbonization of heating[1], encouraging the use of electrically-powered heat pumps. This will have a major impact on the demand for electricity.

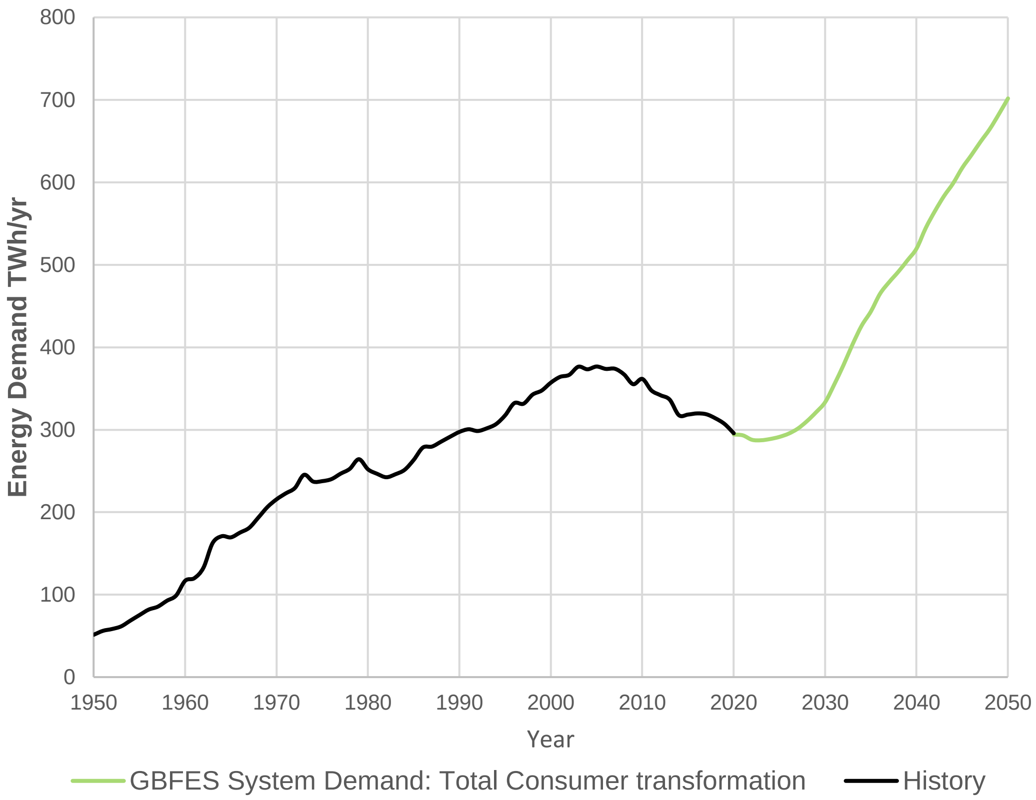
Forecasts for the GB grid show that total energy demand may more than double from 300 TWh to over 700 TWh between now and 2050.

In terms of TWh/yr, this would be even faster than the previous fastest rate of change[2] of demand that was seen during the build-out of the transmission system in the 1950s.

This is a new challenge for transmission and distribution grid owners and operators, where demand has been relatively stable for the last 30 years. The challenge is not just due to the impact on energy requirements, but also because of the impact on the techniques required for management to ensure grid stability.

Substantial new investment in generation capacity will be required, together with energy storage technologies which offer the possibility of smoothing out peaks in supply and demand.

Growth in demand on the GB grid



Graph of historic total generation 1950 to 2020 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1005772/Electricity_since_1920.xls
And forecast 2021 to 2050 from FES System Demand: Total Consumer Transformation Future Energy Scenarios, July 2021, National Grid ESO

1). Plan to drive down the cost of clean heat
2). Historical electricity data: 1920 to 2020

The increasing demand from EVs, and other loads, is the largest in decades. We need to address the challenges to reap the benefits of decarbonization.

NETWORK

Transmission and distribution network constraints

Some part of the GB transmission grid have spare capacity. The size of which varies through the day. This can support expanded demand and provides resilience in the event of faults. However, in many areas the availability of appropriate connection capacity is already a major limiting factor to the adoption of low carbon technologies. For example, the timescale and cost of connection is a major issue in deciding on the siting of wind farms and of public EV charge points.

As both generation and demand increases, network constraints will need to be addressed by significant investment in additional transmission and distribution capacity. This system reinforcement has major cost and timescale implications as GB moves to decarbonize the economy.

DNOs have developed plans in RIIO-ED2[1] to increase distribution capacity to match increasing demand. This includes conventional network reinforcement via increasing physical infrastructure capacity, however this is an expensive and time-consuming process.

Complementary solutions are being deployed supporting Ofgem's vision[2] for a secure, affordable, net-zero system where all connected resources can flexibly respond to available energy and network capacity.

1). RIIO-ED2 business plans: DNOs confirm billions to support 'profound change'
2). Ofgem's vision for full chain flexibility

400%

Some boundaries see peak power flows 400% greater than existing capabilities by 2030

Operability Strategy Report 2022 – need to know

System reinforcement is not a quick or cheap fix; we need to consider regulatory and market design approaches to exploit existing surplus capacity.

NETWORK

Active Network Management

As an alternative to system reinforcement, with the associated costs and timescales, Active Network Management (ANM) is being employed. With ANM, the availability of network capacity for some users is varied over time to fit within the constraints of network assets. Adoption of ANM will either delay the need or reduce the scale and cost of the required distribution grid reinforcement.

DNOs are applying the strategy of "Flexibility first"[1] ahead of reinforcement. Currently this is typically used to manage export overloads from embedded generation.

ANM introduces new control systems for actively controlling power transfer to remain within network constraints. It helps the network run near full capacity while simultaneously reducing the risk of equipment damage due to overloads.

As EV charging and V2G grow, DNOs are planning[2] to use ANM to manage loads on the distribution infrastructure. This will take ANM schemes into the territory of domestic customers.

These **systems need to be resilient, continuing to enable constraint management and avoiding overloading infrastructure, even during and after fault conditions.** This requirement for resilience includes the flexible generation and loads that are being controlled by ANM, which will include V2G and EV charging.

1). Delivering a Flexibility First Approach
2). LV Connect and Manage

"The last mile of the distribution network has previously been all but invisible but companies can no longer afford to have the low-voltage network as a data blind-spot. The rapid growth in disruptive technologies such as microgrids, energy storage and electric vehicles, alongside the increased use of renewables and distributed energy resources is having a major impact on energy network management."

Low voltage Gridkey overview, Lucy Electrical

"We have and are continually rolling out Active Network Management (ANM) in areas of our network with limited capacity headroom which would otherwise necessitate significant reinforcement works. ANM negates the need for most of these reinforcement works or where still necessary, facilitate connections prior to the completion of the reinforcement works, which can sometimes take several years. The ANM schemes work on the basis that the distributed control systems continually monitor limits on the network and then allocate the maximum amount of available capacity to customers in that area based on the date their application was submitted."

ANM curtailment reports, WPD

DNOs already consider the intrinsic value of flexibility of demand and generation; we need to ensure that such assets can be reliably flexed in a predictable manner.

EV CHARGING

Smart vs unmanaged EV charging

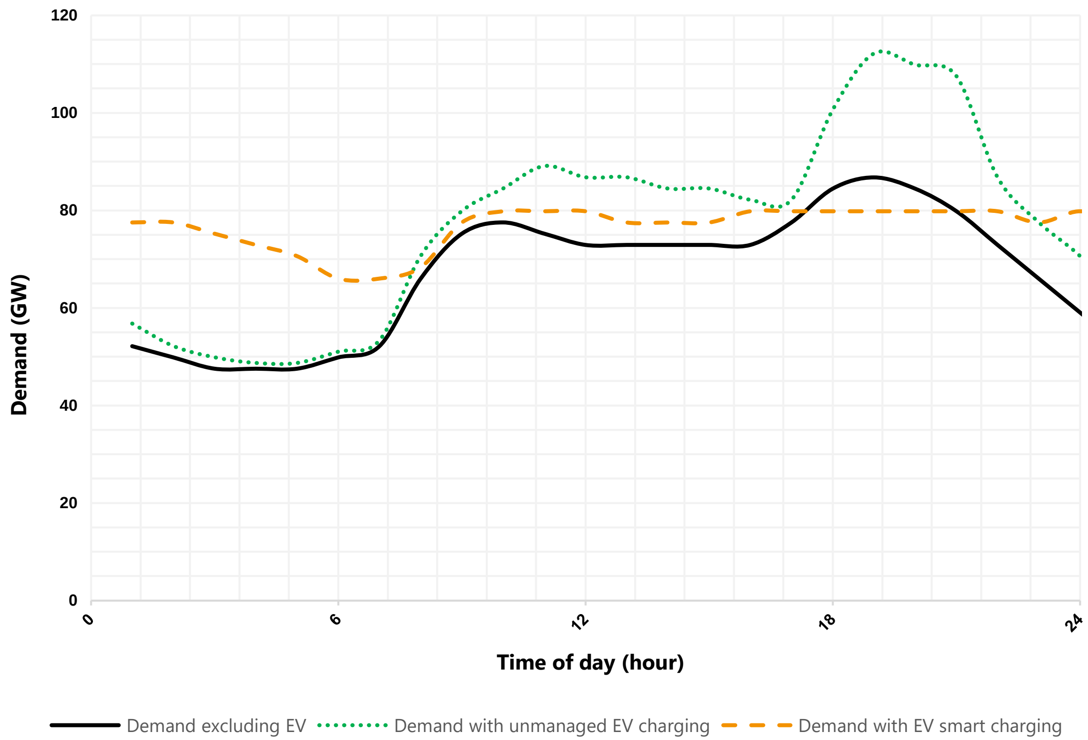
When an EV is connected to the supply, just like a mobile phone, it would normally start charging immediately and only stop when fully charged. Smart charging modifies this behaviour, controlling the timing of the charging.

Smart charging can be a benefit to the consumer as it can lower the cost of charging. Suppliers may provide a lower tariff at some times of day, encouraging time-shifting of demand. This provides a benefit to grid operators by moving some demand away from peak times. **Smart charging can help reduce the need for grid reinforcements or shift demand to a time when generation is lower cost.** For example, by shifting demand from evening peak time to over night, when other sources of demand tend to be lower.

Smart charging can also be used to optimize energy flow in the home. Consumers may choose to charge using power from home PV solar generation, in preference to supply from the grid. This provides an economic benefit where the price paid for import from the grid is higher than the price received from export to the grid.

Smart charging may also be used to address constraints in the system, for example sequentially charging vehicles in a carpark to limit the peak demand to match the supply rating for the site.

Mid 2030s forecast showing the potential for smart charging to reduce daily peak demand



Smart Charging of EVs can mitigate upgrade needs for network and peak generation capacities.

EV CHARGING

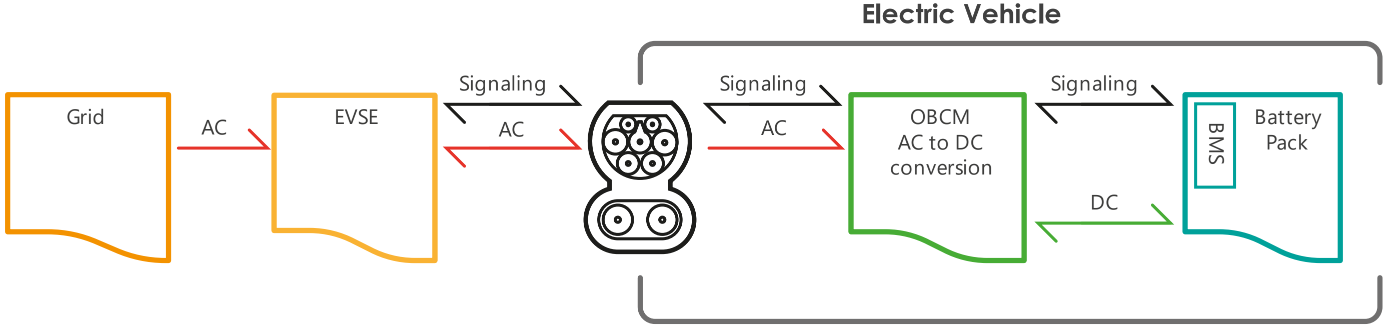
EV Charging System

EV charging (EVC) is the process of taking energy from the grid and storing it in the EV battery. The EV charging system must convert the AC from the grid into DC for the battery, control the amount of power transfer and ensure the safety of consumers.

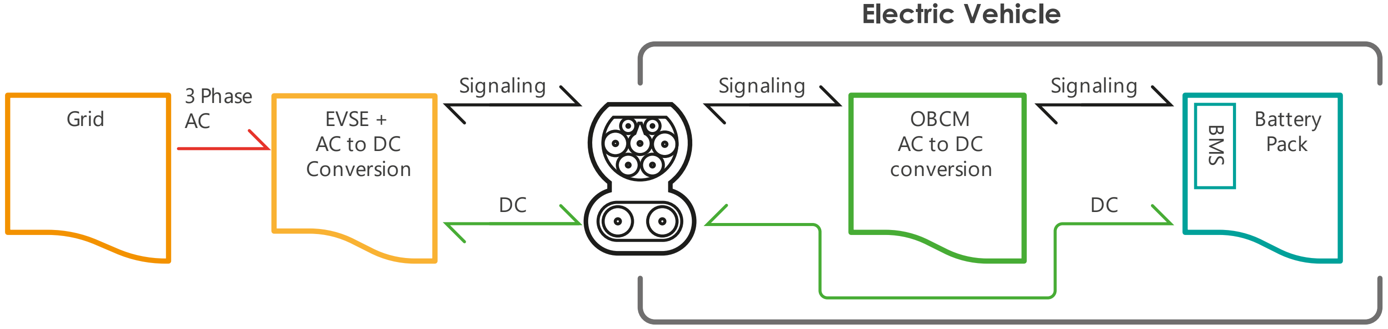
The most common form of EV charging in GB is domestic AC charging, where AC power is supplied to the vehicle via a ChargePoint otherwise known as an EV Service Equipment (EVSE). The EVSE helps ensure safety of the charging process and includes multiple forms of protection. The vehicle uses an On-Board Charger Module (OBCM) to convert AC to DC to charge the battery. **The OBCMs in current vehicle models are typically 32A 7kw single phase**, but some can support up to 22kW or more when connected to a 3-phase AC supply.

For faster charging an off-board, forecourt power converter can be used. This bypasses the OBCM power converter, supplying DC direct to the battery, with typical power being in the range 50 – 350 kW.

Domestic and public charging systems can often be controlled by phone apps via the cloud. Publicly accessible ChargePoints include systems to authorise charging and bill for the service, for example using contactless cards.



7kW domestic single phase **AC charging**



50kW to 350kW forecourt **DC charging**

EV charging includes a range of peak capacities, with many control options; it is important that modelling and mitigations consider this lack of homogeneity.

EV CHARGING

Energy requirements

The amount of energy required to charge an EV depends on factors such as the type of vehicle, distance travelled and speed of driving. **In the UK a typical private EV car may travel 3 miles per kWh and consume approximately 2,500 kWh per year compared to 3,800 kWh[1] per year for a typical home.**

Cold or wet weather has a signific impact, increasing EV energy demand for vehicle heating, aircon and lighting. Winter consumption is typically 30% above average placing additional demand on the grid at the same time of year as electric space heating by heat pumps.

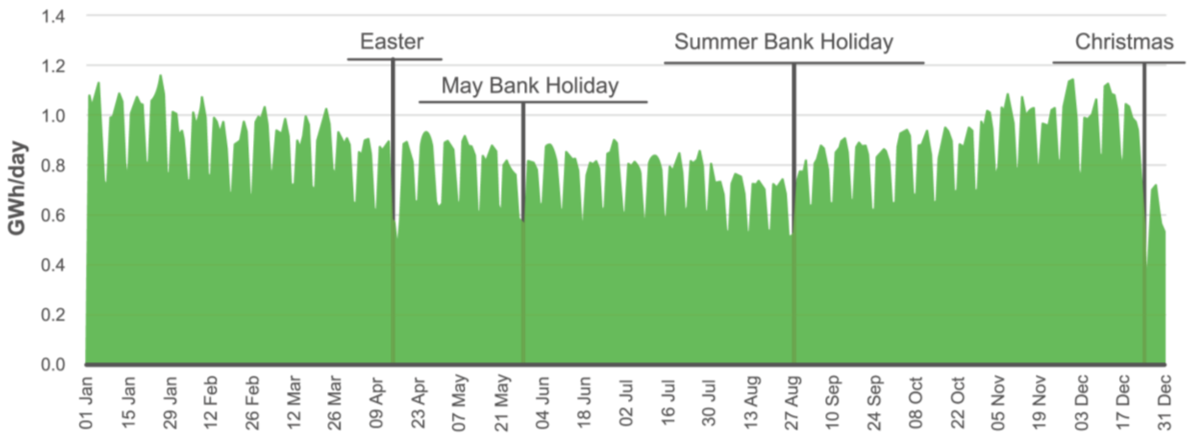
A short power interruption can significantly disrupt the charging process. Some EVSE require manual reset or credit card reauthorization to restart the charging process.

An EV stores energy in its battery, so unlike most electrical devices the vehicle can be used during longer power cut. Obviously however, a power cut will prevent charging, in the same way that a power cut prevents forecourt pumping of fossil fuel.

If the power outage lasts for a significant time, say a day or more, there will be considerable extra demand when power is restored to recharge the depleted EV batteries. This can lead to increased load on the grid when power is restored.

1) Review of the average annual domestic gas and electricity consumption levels

Seasonal variation in energy requirement for EV charging



Based on a profile for a stock of 180,000 EVs, and 2017 temperature profile. EV Charging Behavioural Study, Element Energy

The normal seasonal, and post-fault-recovery, energy profile of the GB grid will evolve significantly with EV mass adoption.

EV CHARGING

Vehicle to Grid

An EV can be considered a big battery on wheels. By mid 2030s a typical capacity may be 100 kWh per EV, about 50% higher than today. Bidirectional EV chargers have been developed that allow power transfer from the EV to the grid. **Vehicle 2 Grid (V2G) can be used[1] to provide grid balancing services, providing power to the grid when supply margins are tight, and charging when excess renewable generation is available**. EV owners may be paid to provide this service or benefit from lower energy tariffs.

An GB industry trial[1] has shown that "Customers participating in the trial can earn as much as £725 a year without needing to do anything except keep their cars plugged in when they are not in use."

V2G has the potential for almost instant (<1 cycle or <20ms) response time for turn-around from full charge to full discharge. In comparison existing pumped hydro takes about 16 seconds to do the same.

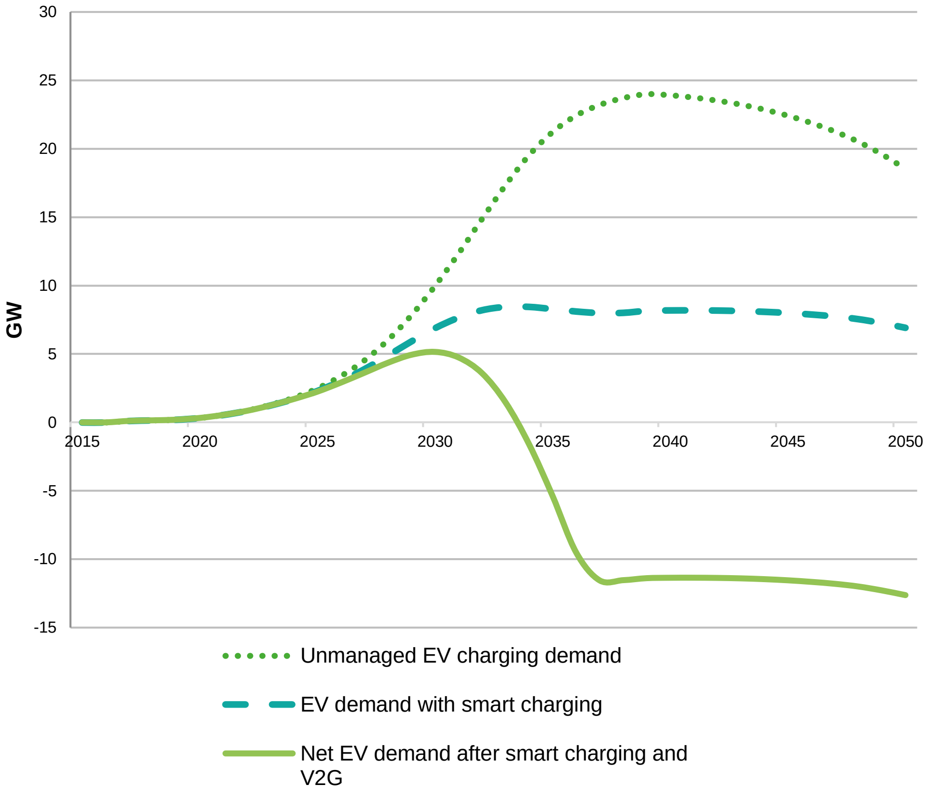
It is very early days for V2G in GB with only initial trials, not large-scale commercial deployment. However, V2G is expected to be supported by most vehicle models in the 2030s.

"Enabling rapid development and maximising the uptake of smart charging and V2X technology" is an Ofgem Priority Area[2].

National Grid ESO are forecasting up to 12 GW net V2G by the late 2030s. This is a major resource equal to the peak capacity available historically from the all GB nuclear powered generators[3].

1). Case study (UK): Electric vehicle-to-grid (V2G) charging
2) Enabling the transition to electric vehicles
3). Nuclear electricity in the UK

Electric vehicle charging system demand during average cold spell winter peak



Future Energy Scenarios, July 2021, National Grid ESO

V2G could mitigate the peak impact of EV charging, and even provide a tool to help manage network constraints and variable renewable generation.

EV CHARGING

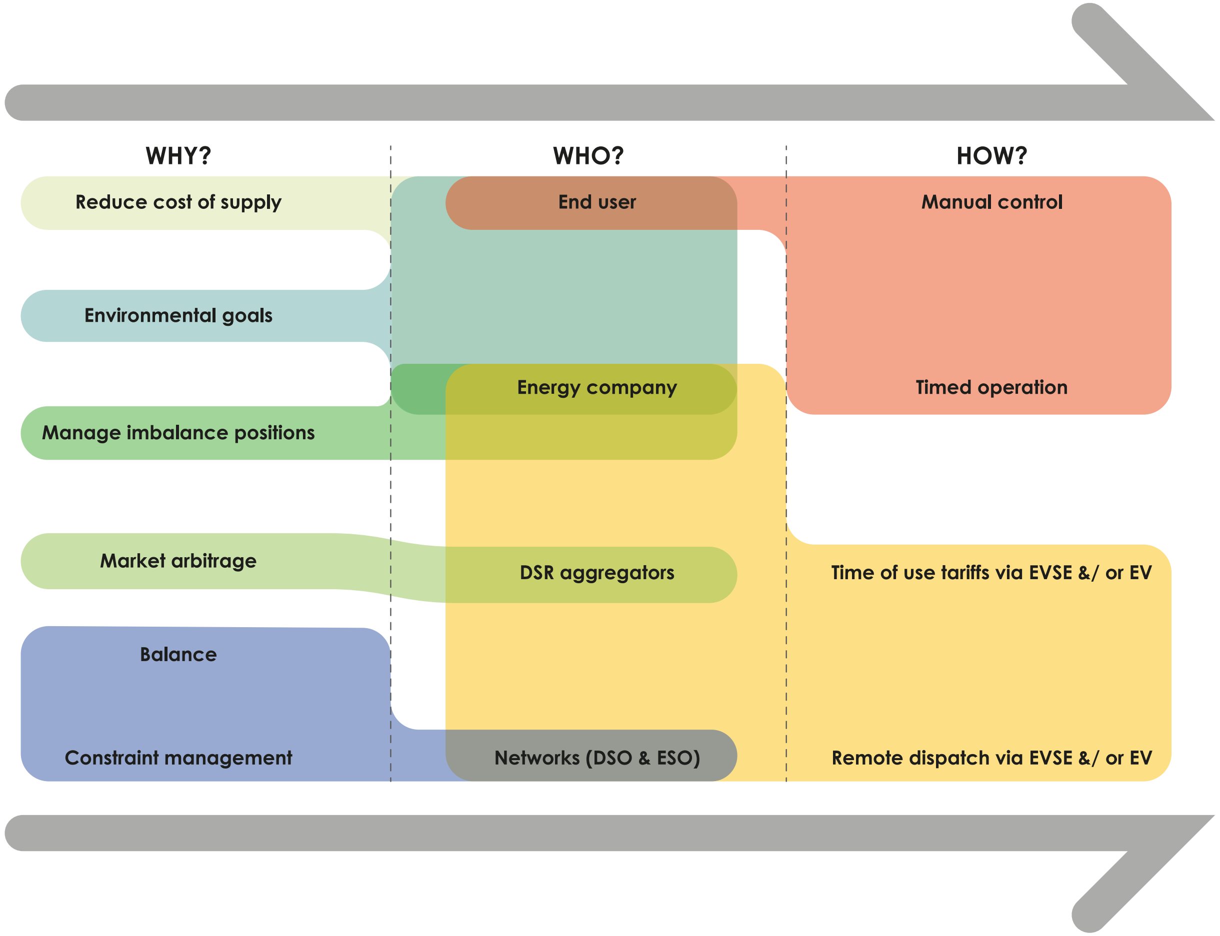
Smart control & aggregators

Smart EV charging, including V2G, will usually be controlled by an automated system responding to factors such as consumer preference, local or national constraints and tariff information to determine when to charge or provide V2G. Collectively these are known as Demand Side Response (DSR) services, and these may take many forms.

Grid operators will define specific requirements for DSR services, typically including factors such as type of service, availability, response time, minimum capacity and geographical region. This is a barrier to entry which means a large number of EVC systems must be combined into a single unit to provide these services to grid operators.

Aggregators can and do provide services to grid operators combining the capabilities of many EVs, along with other assets, into Virtual Power Plants (VPPs) and bidding within the Balancing Mechanism or future flexibility markets. Aggregators provide dynamic tariff information or dispatch instructions to individual EVC to facilitate their individual contribution to the service delivery.

The emerging system will become far more complex than shown right, for example, some EV manufacturers or vehicle lease companies may provide charging as a service, as part of a vehicle lease deal. They may also provide DSR services to grid operators.



Market evolution is presenting many pathways to aggregate small EV/V2G assets, whilst those assets respond to many factors.

EV CHARGING

Smart charging communication

Smart charging is an essential tool in the future management of the grid. To maximise the benefit to consumers and grid operators, real-time communication is required allowing EV charging and V2G to respond dynamically to grid operational needs.

This introduces a dependency on these communication systems for grid management. Reliability and security is an important consideration. **A successful cyber attack or a wide-area failure of the communication system could significantly degrade the DSR services available from EVs.**

Communication system bandwidth and latency also impact the type of DSR services which could be controlled. Some DSR services may be based on half-hour Balancing Mechanism intervals, where others may rely on fast communications to make second-by-second adjustments to manage local constraint.

The choice of communication technology has a major impact on how EV DSR will respond after power outages. A broadband router or cellular modem may take tens of seconds to several minutes to reboot.

The government and UK mobile network operators have agreed to phase out 2G and 3G mobile networks by 2033 in order to free up bandwidth for 5G and future 6G services. This includes Telefónica (O2) who provides the Smart Meter communications for the Central and Southern regions of the UK.

New measures to boost UK telecoms security, .gov.uk website

““Energy UK is clear in its position: mandating the Smart DCC[1] as the enduring solution for smart charging is not the way to go. We need to avoid GB-centric solutions when the market for EVs and ChargePoints is a global one; we must ensure that any solution avoids single points of failure; we should seek solutions that work for both the domestic and non-domestic sector; we must prioritise approaches that increase rather than restrict functionality; and we need to allow companies that are pushing the limits of technology to continue to do so, so that smart charging remains synonymous with innovation, customer-focus and an excellent user experience.“

1). Smart DCC is a monopoly company that operates under the Smart Meter Communications Licence.

The future of electric vehicle smart charging, April 2021 Engage for Energy UK

It is important to recognise that the performance of EV/V2G DSR (and other smart loads) is highly dependent on communication links.

EV CHARGING

On-site coordination

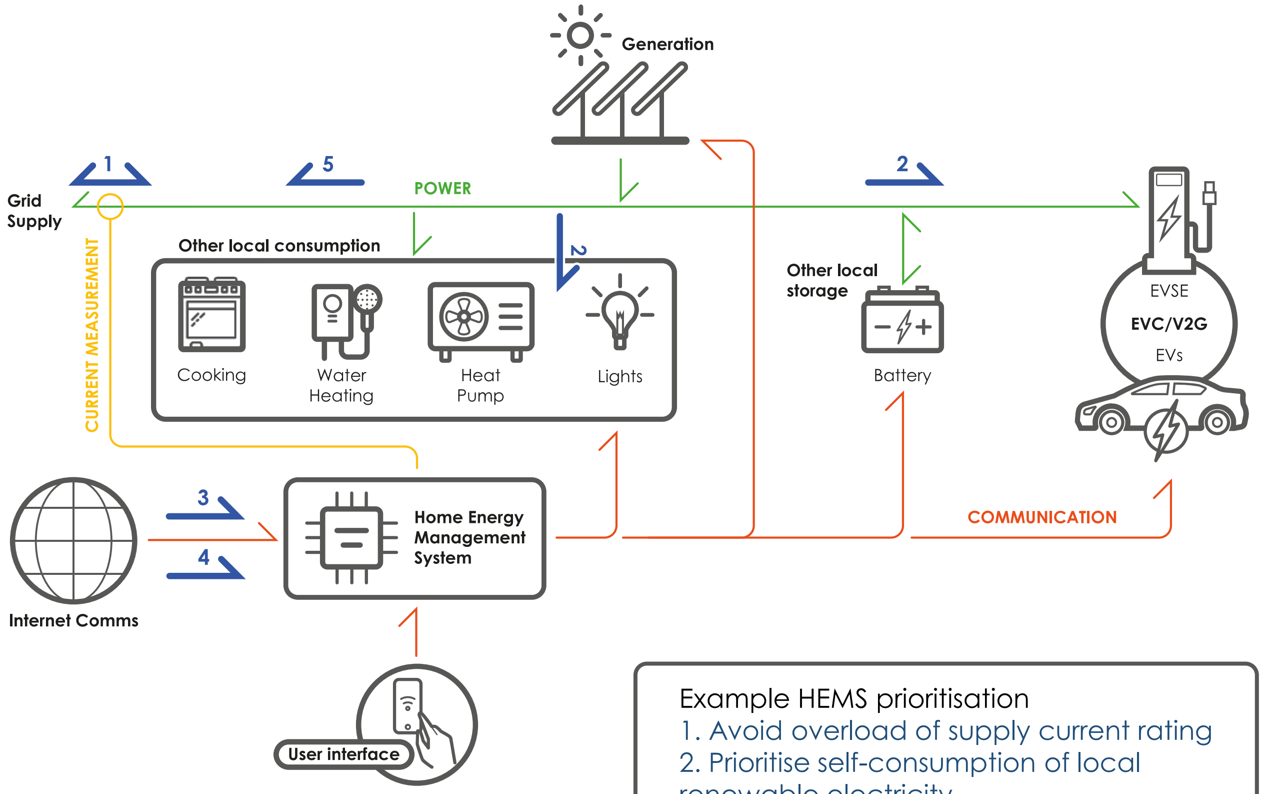
More advanced charging control systems can help address a building or site constraint, for example by reducing EVC power to avoid overload of the supply to a house when charging, heating, cooking and showering are required simultaneously.

This type of system has to be very fast acting, to avoid operation of the building supply cut-out (fuse). It must respond in fractions of a second to increasing loads and be highly reliable, so this core control function must be on-site, not depend on communication to a remote server.

Higher-end products can also respond to output from local generation. For example, a smart EVC may minimise energy export from domestic solar PV, since EV charging will be more economically beneficial than "spilling" energy to the grid at a low sell price.

When a building or home has multiple such systems, for example two EVs, a smart heat pump and solar PV control becomes more complex. In some cases (see diagram) a central Home Energy Management System (HEMS) may be used to coordinate operation of all the on-site smart appliances.

In other cases (not shown) smart devices may not be coordinated by a HEMS. Each may have direct internet communications and independently try to optimize for their own priorities, **there is a risk of control instability if each system tries to optimise performance independently.**



Example HEMS prioritisation
1. Avoid overload of supply current rating
2. Prioritise self-consumption of local renewable electricity.
3. Respond to VPP dispatch
4. Respond to ToU tariff
5. Minimize export to grid

On-site coordination can facilitate installation of multiple LCT devices in homes, without the risk of overloading the supply cutout.

EV CHARGING

Mass Charging Sites

Most EV charging in GB is predicted to occur at the home, but there will be large-scale charging sites supplying up to tens of MW for

- Single car parks
- Bus depots
- Goods vehicle transport hubs

These sites will typically

- Have a dedicated 3-phase MV or HV supply
- Use a single model or small range of EVSE
- Be coordinated by a single site operator
- Employ local constraint management via a plant or site controller
- May include local battery energy storage to help support peak loads and provide DSR services to grid operators
- In the case of a workplace, may help provide backup power, via V2G, to the office/factory as an alternative or supplement to a UPS or generator.

These sites, by concentrating load at one location, introduce new opportunities together with new risks.

"Energy Superhub Oxford will be the world's first transmission-connected electric vehicle (EV) network. This means it will connect directly to National Grid's extra-high voltage system, and bypass the local distribution network. It will provide up to 25MW for EV charging which is enough power for over 100 ultra-rapid chargers."

Energy Superhub Oxford

"Tech partners seek to turn electric school bus batteries into 1GW virtual power plant"

Energy Storage News, July 2021

The EV transition will bring a range of small, medium & large loads across commercial & public charging sites, with different load profiles and local challenges.

EV CHARGING

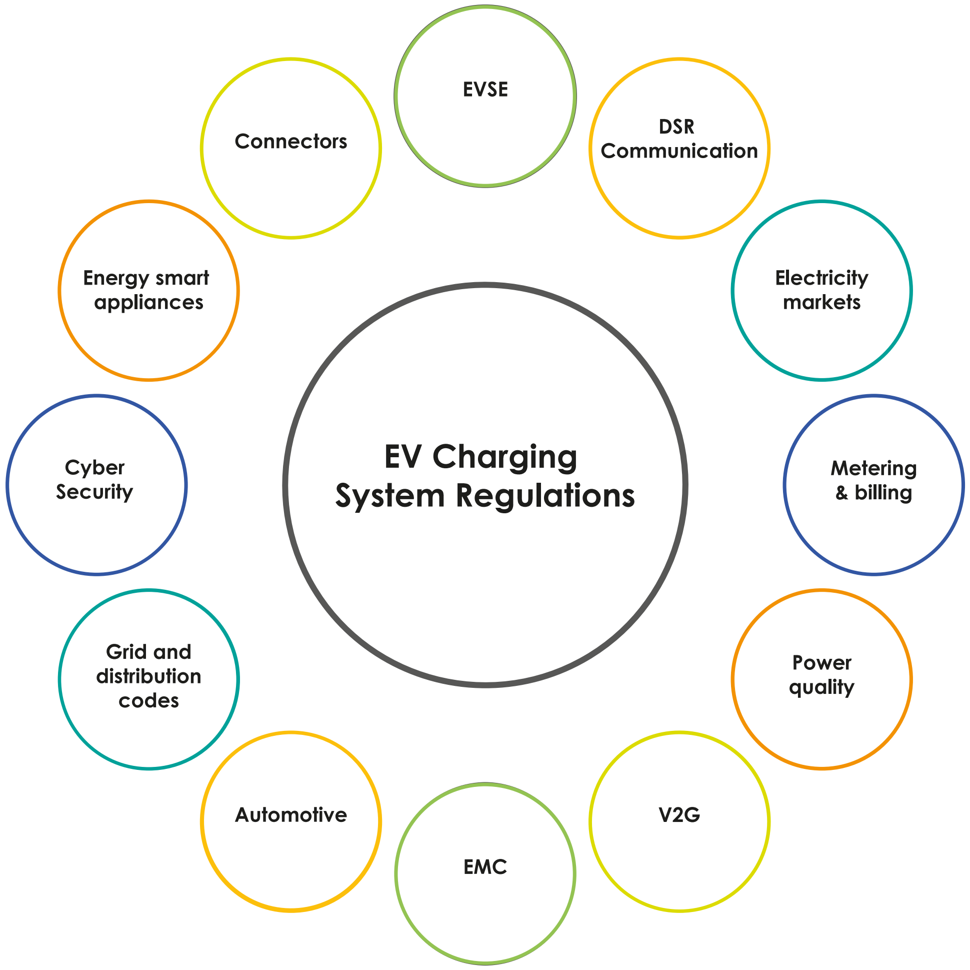
Rules and regulation

The EV charging technology and market are subject to a wide range of regulations addressing factors such as safety, interoperability, security of supply, fair and efficient market operation.

Continuing evolution of regulation is an essential part of the transition to net zero. For example, it is expected that the adoption of ISO 15118 *Road vehicles -- Vehicle to grid communication interface* is an essential step to support wide scale roll-out of V2G as it will provide a common interface adopted by most vendors.

Significant global variations remain. Some smart charging systems are currently based on propriety technology. There are moves to standardise EV DSR as part of a wider DSR capability, for example BSI PAS Operational framework for energy smart appliances in a demand side response energy supply system[1].

Historically, regulation of generators has been stricter than regulation of loads (for example, the fault ride-through requirements). However, **as DSR becomes a key service to the grid it is likely that detailed regulation and careful management will be required to ensure security of supply.** This will include many aspects of the chain from EV to EVSE, HEMS and aggregators.



1). Operational framework for energy smart appliances in a demand side response energy supply system

It's time for regulators to ensure that smart EV charging and V2G can leverage their inherent flexibility without unintended consequences.

THE NEED FOR REINFORCEMENT

GB LV network design

The majority of EV charging in GB is forecast to be at home. This report concentrates on the GB grid where domestic supply was historically designed for

- 230V Single phase
- Supply cutout 100A (23 kW) or lower
- 2kW After Diversity Maximum Demand (ADMD)
- AirCon and domestic electric heating being unusual
- Substation supplying about ~100 houses

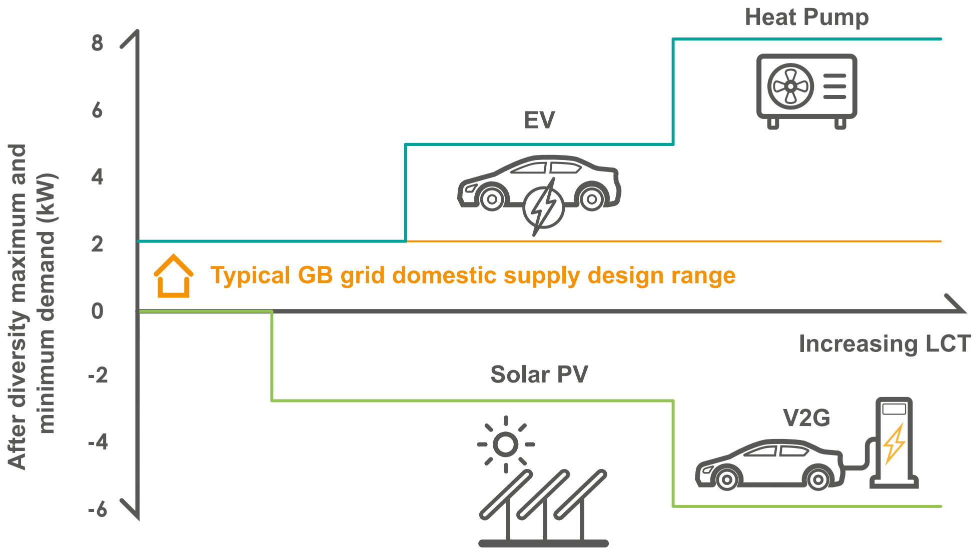
Higher capacity 3-phase supply is rarely available to domestic consumers, but available broadly within commercial premises.

An Ofgem presentation[1] in 2011, quoted right, described the historic design intent for GB grid. It highlighted the challenge presented by the increased power demand for electrification of transport and heat, combined with generation from solar PV. Not all EV owners will choose to charge their vehicle at the same time, so ADMD is typically around 3.5kW for a 7kW charger. V2G will further add to thermal and voltage control challenges in the LV networks.

Low carbon technologies (LCT) place demand on infrastructure far beyond the original design intent, requiring careful management and selective upgrades.

There are significant differences between countries which must be recognized when making international comparisons. Also, many products sold in GB are designed for international markets, so will have features designed for a wide range of markets. For example, EVs are already being manufactured with 40kW V2G capable OBCM[2] for markets where 3 phase supply is common.

1). From DNO presentation, Ofgem
2) A Review of Bidirectional On-Board Chargers



> "The LV system was designed for a thermal rating and voltage drop caused by a domestic load of 2kVA ADMD. Our networks were originally designed to be passive and supply load in one direction, it was not designed for voltage rise. Cleaner energy is pushing our system beyond their design parameters."

From DNO presentation, Ofgem

EVs and electric heating (solar PV and V2G) introduce a paradigm shift in diversified load (generation) for domestic and small commercial consumers.

THE NEED FOR REINFORCEMENT

Distribution network reinforcement

ANM and smart charging alone will not provide adequate transmission and distribution capacity to supply new demand coming from LCT.

Looking beyond detailed plans prepared by DNOs for RIIO ED2 to the late 2030s, with mass electrification of heat and transport, substantial network reinforcement will be required with a particular emphases on the MV and LV network.

The need for reinforcement will vary across the country. There is significant regional variation in existing installed capacity, as historically some DNOs planned for higher penetration of storage heating so built networks to support higher ADMD. EVs uptake will have a disproportionally large impact in rural areas, where driving distance greater and often the LV grid is weaker.

Network reinforcement is expensive and time consuming, often involving the need to gain access to consumer premises, dig up roads and, on occasions, purchase new sites and secure land rights such as wayleaves.

During reinforcement activity should all new buildings support 3 phase for future growth of LCT? And all retro fit also be 3 phase? DNOs are starting to go down this route.

EVs will place new demands on the grid..

Transport Decarbonisation Director Graeme Cooper has long championed the adoption of EVs and is confident the grid can support the extra demand for electricity this transition will create.

"There is definitely enough energy and the grid can cope easily," he explains. "The growth in renewable energy means this is not static and smart metering will make this more efficient. For example, the growth in wind power from the extra offshore wind farms being developed will adequately meet the future demand for electrifying transport – an extra 100 terrawatt hours from our current 300 terrawatt hours consumed."

Can the grid cope with the extra demand from electric cars? National Grid blog post

Which will need timely upgrading.

Distribution network capacity:

"The volume of new demand and generation, combined with the effect of customer consumption patterns becoming more dynamic and complex, will push power flows well beyond what the distribution network is currently designed for. These changes impact every voltage level: from LV networks, to which the LCTs needed to deliver Net Zero primarily connect, to HV and EHV networks, which supply the LV networks and must accommodate increasing levels of DG. **Without radical intervention, these changes will cause thermal, voltage and fault level constraints which dangerously overload the network.** These will lead to customer supply interruptions, delays in delivering customer requirements, shortening of network asset life, higher overall costs for customers, and possible safety concerns.""

Distribution System Operator Strategy SPEN

We must take care to separate growth in GB annual energy demand from our ability to locally balance supply & demand, distributing energy via the T&D grid.

THE NEED FOR REINFORCEMENT

Rapidly changing nature of loads

The generation mix on the GB grid has changed rapidly[1] over the last 20 years with the deployment of renewable generation. The total demand for electricity has been slow to change over the past 20 years but is expected to change rapidly over the next 20 years. decarbonization of heat and transport will lead to an increase in demand and generation.

There will not only be a doubling of energy demand. Smart control systems will be used to help balance supply and demand and manage constraints. Most high-power loads will be converter-connected, with variable speed drives for heat pumps and software-controlled solid-state AC to DC conversion for EV charging.

A large number of devices will have a complex response to grid transient events, with under and over-voltage limits, delayed reconnecting times and dependency on software control and smart communication systems. This presents a significant modelling challenge for engineers assessing grid stability, resilience and the need for reinforcement.

1). Historical electricity data: 1920 to 2020

"It is impossible to predict the exact mix of technologies, models and behaviours that will evolve, but analysis presented by the Committee on Climate Change suggests extensive electrification, particularly of transport and heating, with all electricity produced from low-carbon sources. Given the resulting predicted doubling or quadrupling of electricity demand, the pace, **scale and nature of the change are completely outside recent sector experience."**

Electricity Engineering Standards Review, December 2020, Independent Panel Report

"Understanding the risk of control system interactions as converter based generation increases will requires detailed electro-magnetic transient (EMT) studies to be carried out which in turn requires more detailed modelling of the network as well as the converters." This was stated in the context of large generators, but it will also apply to mass high power domestic converter based technologies such as EV chargers.

G-PST/ESIG Research Agenda for Transformed Power Systems

Whilst the type of generation has changed significantly in the last 20 years, the types of load will change rapidly in the next 20 years.

THE NEED FOR REINFORCEMENT

Summary

The challenges and opportunities presented to the grid by EV charging and other LCT as we move to NetZero are profound.

- Doubling of energy demand in 20 years leading to the need for more generation capacity, ANM and grid reinforcement.
- DSR from consumer devices, such as EV charging, along with its communication and control systems, will become a critical part of national infrastructure.
- An increasingly wide range of organizations will be involved in grid balance systems and services adding complexity.
- Power converter connected loads will significantly impact the short-term stability of the grid, bringing potential issues and opportunities.
- V2G has the potential to provide 7 times the power (12 GW) of the largest current storage system in GB (Dinorwig 1.8GW) and a turn-round time from charge to discharge of <1 cycle rather than 10 seconds+.

It is difficult to overstate the scale of these changes, and depth and breadth of the influence on day-to-day grid operations.

“By the end of this decade we won’t be dispatching generation to meet demand as we have done for the last 40,50.. 100 years. We’ll be dispatching demand to meet the generation”

Julian Leslie,
National Grid ESO at COP26 From Twitter

We need a **revolution** in how and when we use energy.

“This is essential to hitting the UK’s net zero climate goal while keeping energy bills affordable for everyone. The prize is huge. According to the Carbon Trust, it will save households and businesses an estimated £16.7bn per year by 2050 as we transform the way we generate power, drive our cars and heat our homes. These savings are essential to maintaining public support for net zero. To realise them, we need everyone who can to play an active part while protecting those who can’t.”

“If everyone charged their electric vehicle at the same time on a winter’s evening, the costs would be huge. We would need to build lots of expensive back-up generation and grid capacity, especially when renewable generation is low because it’s not windy or when it’s dark. If instead people charged their car at different times, we can avoid some of these costs.”

Jonathan Brearley - Ofgem Chief Executive

The coming growth of load and storage are huge. We should not underestimate the challenges or the potential benefits of V2G!

CHAPTER 5

Challenges for charging system suppliers

This section highlights issues related to power transient events, and smart charging communication issues, which may directly impact consumers causing them to seek solutions from charging system suppliers.

INTRODUCTION

Who is responsible?

The core of Project REV is focused on the impact on the GB grid energy at System Operator level.

This section considers the opposite end of the system; the direct impact on consumers. If a charging system does not behave as the consumer expects the suppliers of the system are likely to be the first point of contact.

This may include
- EVSE manufacturer
- EV manufacturer
- Public/workplace charge point operator
- Energy retailer
- Aggregator

When there are problems, it may not be immediately clear where the consumer will look for support or who should the consumer hold responsible? The objective of this section is to highlight potential issues to the broader industry with the aim of mitigating them thus minimising impact on consumers.

All the topics raised in this section are based on issues related to grid transient or communication system events.

IMPACTS ON CONSUMERS

Changing regulations

Although EVs and smart charging systems are already on the market, regulations in this area are evolving rapidly. For example, UK Government Statutory Instruments associated with the Electric Vehicles (Smart Charge Points) Regulation 2021[1] were approved 15th December 2021, comes into force 30th June 2022 and revisions are planned ahead of 2025.

A substantial array of other national and international regulations apply to the components in smart charging systems. These will continue to evolve as the technology and use cases develop, for example allowing mass adoption of V2G.

Both manufacturers and consumers should be aware that regulation changes to address grid management issues can be related to the security of electricity supply. If serious issues are identified, regulatory changes may be rapidly introduced and/or could require update of installed products, as happened with the Accelerated Loss of Mains Change Protection program.

Manufacturers need to be aware of the need to plan for ongoing changes and consumers should be aware of the need for ongoing updates from manufacturers and smart charging system operators to avoid early obsolescence of systems.

1). Electric Vehicles (Smart Charge Points) Regulation 2021

"Huge fines and a ban on default passwords in new UK law"

BBC Link to BBC Report

"Regulations to be reviewed at least every five years to ensure continued suitability. In the short term, it is likely a review will be necessary ahead of the five-year standard review cycle. This is to ensure the legislation remains aligned with the Phase Two intervention planned to be implemented ahead of 2025. Specific requirements including the default charging mode will also be kept under review, to determine if market conditions still necessitate their inclusion."

The Electric Vehicles (Smart Charge Points) Regulations 2021 Impact assessment

With some forethought, building past "minimum viable" product designs, we can avoid frustrated customers and tarnished brands as standards evolve.

IMPACTS ON CONSUMERS

Failure to charge

The primary requirement from the consumer is that the vehicle should be charged ready for use when required. The charging process should be reliable, even when there are grid voltage or frequency fluctuations.

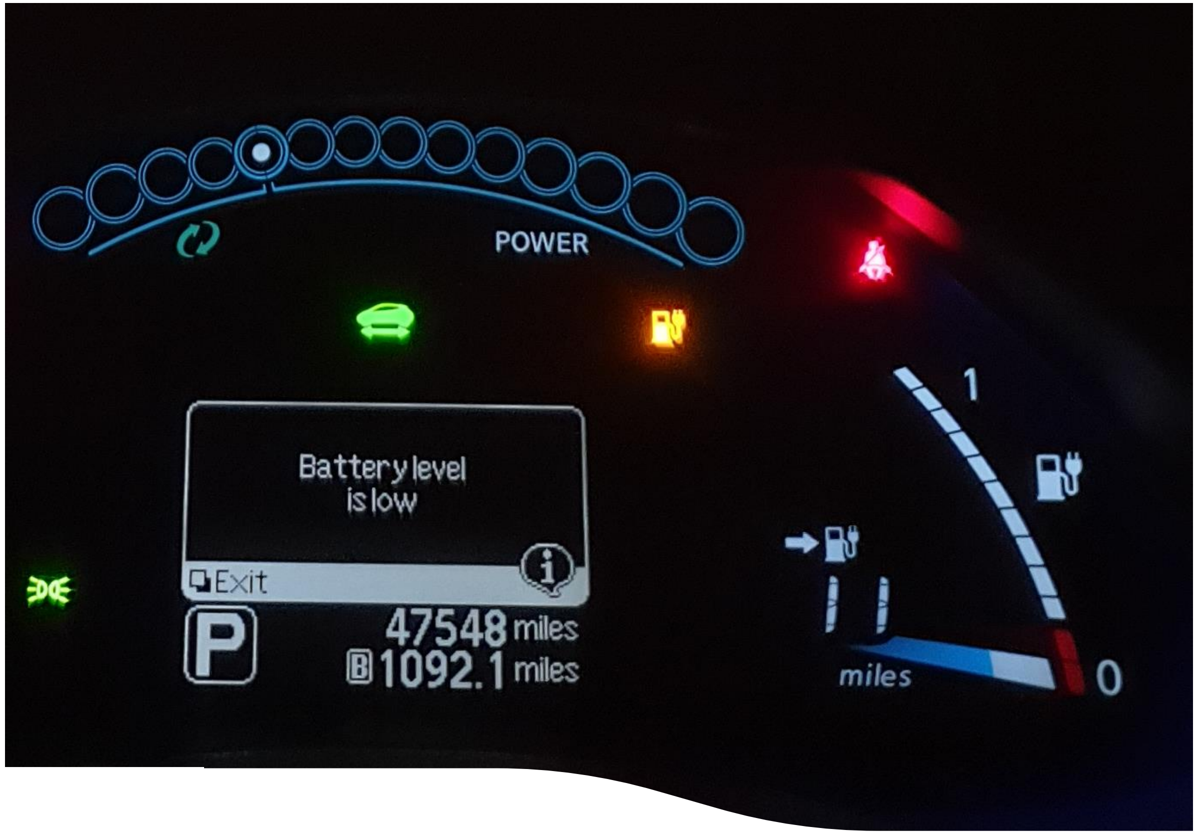
System performance seen by the consumer is the combined effect of power quality, EV and EVSE fault ride-through performance, and additionally for smart charging the communication and the suppliers' systems.

Review of product specification and testing has shown that some non-smart charging systems do not automatically recover after a:-

- Short power outage
- Voltage sag
- Over-voltage

The user may be required to unplug the vehicle and reset the EVSE before charging will recommence. This risks consumers arriving at their vehicle to find it uncharged.

Smart and public charging can be even more complex as it introduces a dependency on communication for charging including billing, leading to a greater chance of an uncharged battery for the consumer. Good fault ride-through is important for the consumer experience.



Fluctuating grid conditions are inevitable. To maximise customer experience, it is vital that manufacturers consider fault ride-through and post-fault recovery.

IMPACTS ON CONSUMERS

Unexpected costs

Failure of smart charging can lead to unexpected costs for consumers. For example, a smart charging system may default to immediate, unmanaged charging as soon as the smart charging communication system is not available, for example due to a DDoS attack or ISP system failure.

This can add significantly to the cost for the consumers, especially where they use a ToU tariff, where peak rates may be ten times off-peak rates. If the issue impacts a significant number of vehicles at the same time, it can be detrimental for the grid operator also, as peak load will increase unexpectedly.

This type of issue may not be immediately apparent to the consumer, the ChargePoint operator, aggregator, energy supplier or grid operator. For some of these parties there is a risk of it going undetected for a long period of time.

The ability for systems to ride though short smart charging communication problems is important, as is reasonable fall-back behaviour and notification of persistent problems.

It is critical that smart charging systems engineering teams consider inevitable issues with communication reliability.

IMPACTS ON CONSUMERS

Power cuts due to smart charging failure

Wide area loss of communication systems or an outage of a large aggregator's control system could impact many consumers at the same time.

- What will EV charger systems do in this situation?
- Will the EVSE user interface still show useful information?
- Will the phone app still operate to provide status information?

Consumer preference may be for the system to rapidly default to full charge, so their vehicle will be available for use if the issue persists. However, for a grid operator this could be the worst-case option as it could lead to load steps and system overloads, especially with mass EV adoption where the EV forms a key part of an ANM scheme.

In a local area this rapid loss of diversity and increase in load has the potential to physically damage local grid infrastructure leading to power cuts for consumers. If the communication or aggregator system outage were to happen on a national basis there is a risk that the surge in demand could trigger Low Frequency Demand Disconnection (LFDD), leading to the risk of regional blackout.

EV charging system performance when smart control systems fail needs to be carefully considered.

The implications of ANM and aggregation failures could be severe, unless appropriately mitigated.

IMPACTS ON CONSUMERS

Maloperation of V2G

V2G operation will slowly discharge the EV battery. This will normally be controlled by a smart charging system, such that the battery is adequately charged when the consumer next requires the vehicle.

If there is an outage of the smart V2G control system, there are two potential extreme outcomes:-

1. V2G may continue until the battery is flat. This V2G operation would lead to a lower state of charge or flat battery when the consumer returns to the vehicle.
2. The V2G system may immediately stop providing power to the grid. If this were due to a wide area outage the rapid disconnection of large number of V2G system could exceed the largest secured loss of generation on the grid, leading to LFDD.

As large scale V2G systems are designed and deployed, the systems must be designed to provide performance which is acceptable for both consumers and grid operators.

Image is an illustration of a V2G charger. This model/ manufacturer it is not intended as an example of this problem.

V2G can provide significant benefits to consumers and the grid; however the potential impacts of failure need to be considered and mitigated.

IMPACTS ON CONSUMERS

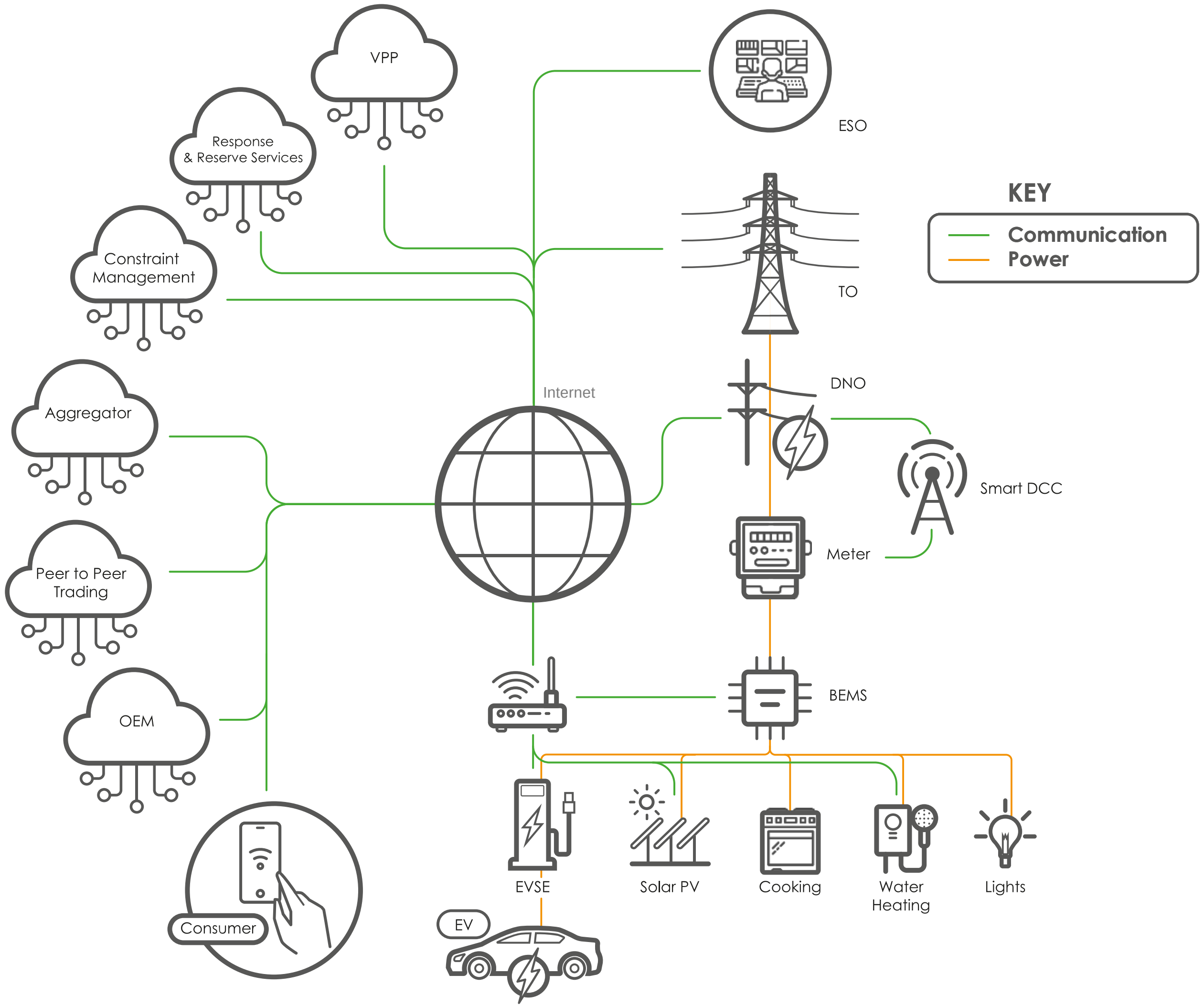
Undesirable Interactions

A few early adopters of EV smart charging system have reported issues with multiple control systems fighting against each other. For example, smart charging EV control by an aggregator conflicting with a home energy management system trying to prevent overload of the supply to the house from combination of EV, heat pump and other domestic loads.

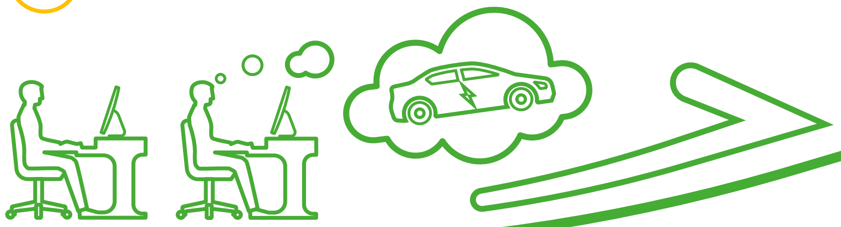
Typically, this may result in rapid start/stop charge cycling as the aggregator enables charging, but the smart EVC then stops the charging to prevent overload. This cycle may repeat many times until other loads in the house are low enough to allow charging. Rapid cycling will charge the battery slowly, if at all, and may cause excessive wear on EVSE contactors leading to premature failure.

More complex interactions are envisaged as multiple independent control systems may allow EVs to contribute to ANM for DNOs and various balancing services for ESO, while a local control system targets zero net PV export and prevents incomer overloads. The complex interaction of multiple control needs to be considered during system design.

Good consumer experience is dependent on masking the complexity, whilst making the system operation intuitive and reliable.



EV charging will utilise local and remote control signals; however, the detail of interacting controls is complex, challenging for both consumers and grid operators.



CHAPTER 6

Challenges to grid operators from large scale EV adoption

This chapter presents the core findings of Project REV WP1. It describes a wide range of issues associated with EV charging that may have a detrimental impact on grid operators. These are summarized and prioritized in the final chapter.

CHAPTER CONTENTS

INTRODUCTION

Simultaneous behaviour from Multiple EVs

In Project REV we are considering the potential impact of large number of EVCs changing their load on the grid at about the same time, say within 10 seconds or so. This is a much shorter duration than existing consumer-controlled events such as evening peak. These simultaneous changes are of interest because many chargers changing state at the same time (within a few seconds) could have an impact on grid stability.

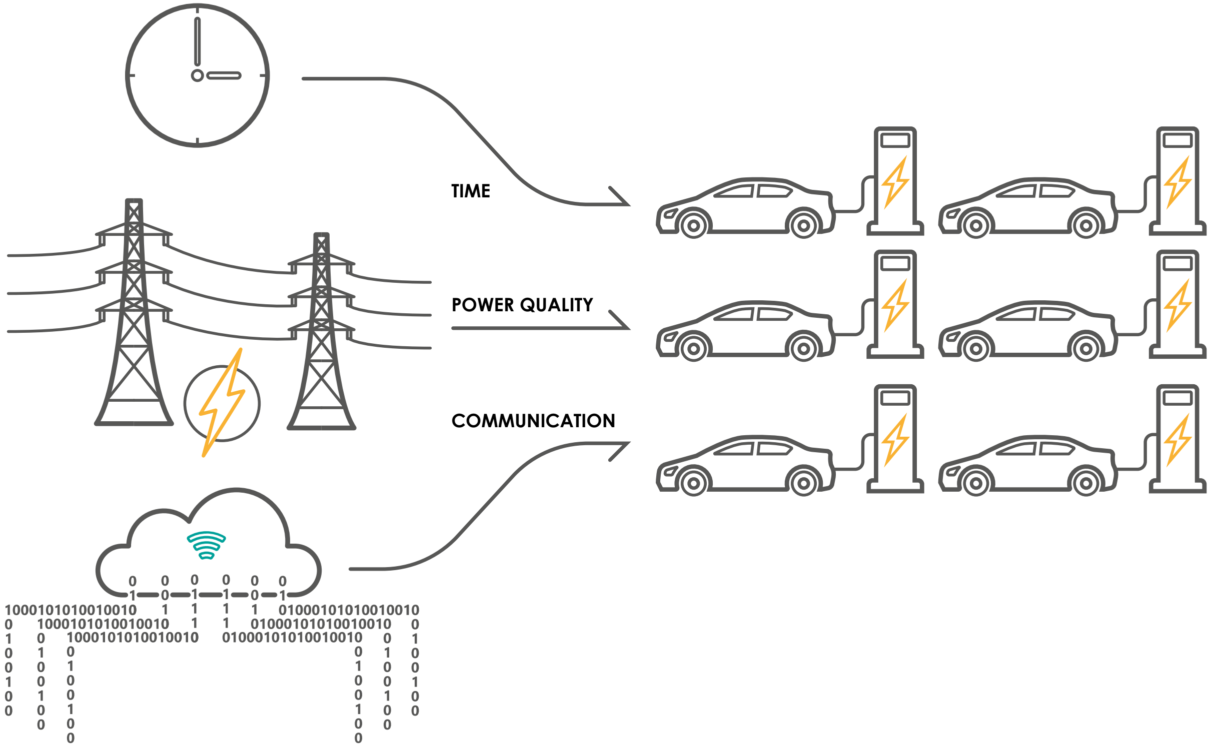
Multiple EVC may act at the same time in response to

- a specific clock time e.g. a time of use (ToU) tariff may cause multiple EVs to start charging at midnight or stop charging at 07:00.
- changes of power quality; grid voltage, frequency or phase e.g. a voltage sag could cause many chargers to stop charging at the same time.
- commands received over a smart charging communication system e.g. An aggregator may send an instruction to tens of thousands of EVs to start or stop charging.

In Project REV we have not considered very rare, but potential high impact events such as

- High Altitude Electromagnetic Pulse (HEMP)
- Space weather events impacting communication and producing Geomagnetic Induced Currents (GIC)

Potential cause of simultaneous response from many EVs



There are lots of drivers of simultaneous EV charger response. Many occur in "normal operation", but others are related to fault conditions.

POWER STEPS FROM EVC & V2G

Steps synchronized by clock time

Grid operation is normally based around slowly changing supply and demand which is predictable. More rapid changes can occur when, for example, a generator trips or there is a large TV pickup. Software controls in smart charging systems create a risk of large, fast, time synchronized load steps.

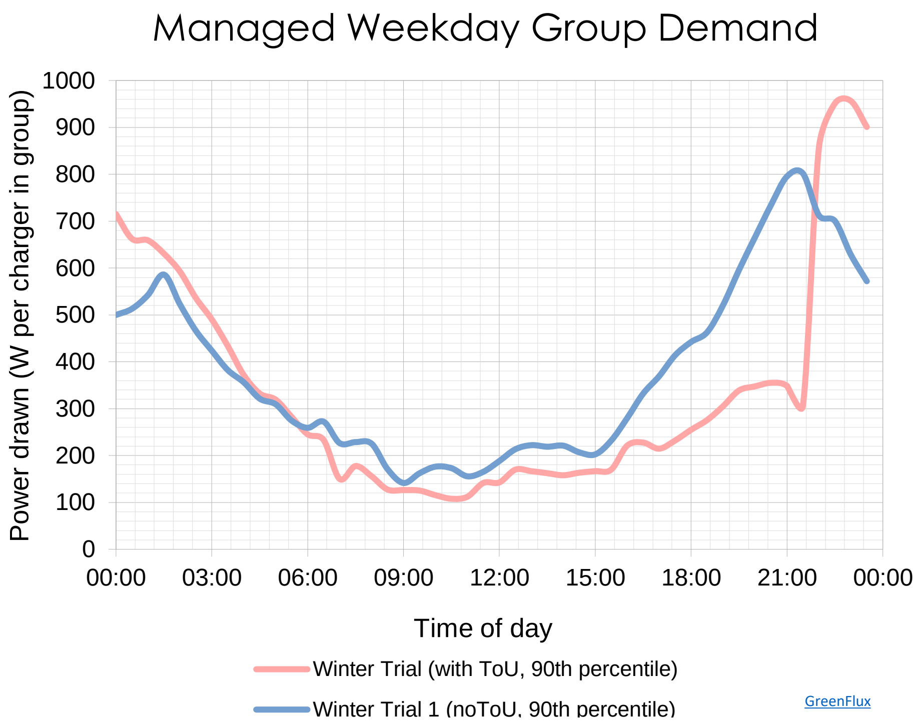
For the purposes of this analysis, we consider a step change as a rapid change of EV load or V2G over a period of 10 seconds or less.

Most clocks used for smart charging control are synchronised via the internet, with typical errors under a second. This leads to a greater risk of large time-related load steps, compared to manually set clocks, which may be several minutes out of synchronisation.

Smart EV charging introduces many potential sources of time-synchronized power steps:

- Time-of-Use tariffs, with steps at the half-hour boundaries between settlement periods
- Consumer preference (or predefined software option) to set charging times in "round numbers", e.g. 00, 15, 30, 45 mins.
- DSR/Aggregator/ChargePoint/VPP control actions and response to dispatch triggers
- A step change in the input to aggregator algorithms, e.g. a changed weather forecast, ESO margin notice
- Clock-related bugs, eg Clock Change, Linux time epoch 2038[1]
- Timed software updates
- Other software bugs
- Cyber attack

1) The year 2038 problem



Time of use tariffs for EV charging can produce rapid step change.

EVC and other DSR will respond to ToU tariffs quickly, potentially leading to large steps in demand.

SYGENSYS

POWER STEPS FROM EVC & V2G

Size of steps

The grid is managed to ensure that supply is maintained after a range of fault events, which are defined in the Security & Quality of Supply Standard. Frequency response and reserve is carried to cover the anticipated single largest loss of infeed or outfeed (export) from the grid

One EV is a small load, but a simultaneous change by many EV chargers can combine to have a regional or national impact. With the volumes of EVC and V2G forecast for 2035, any of the potential causes of steps only needs to affect a relatively small proportion of the large number of EV chargers/V2G simultaneously to be significant for grid operability.

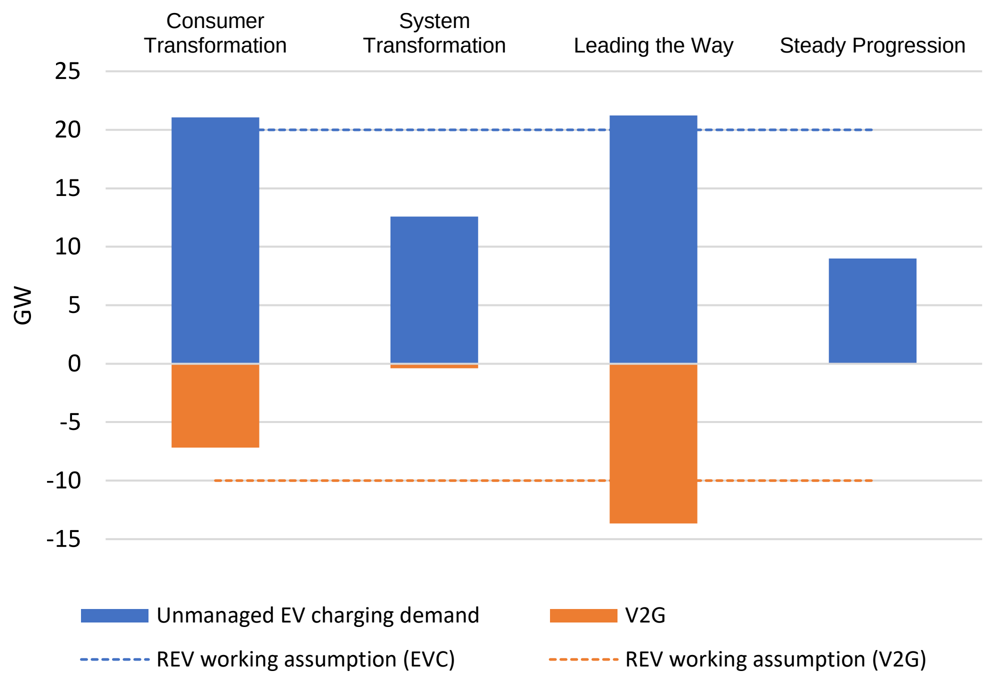
It is important to note that the FES 2021 figures for Unmanaged EVC Demand (see right) already include a high level of diversity; with 7kW per EV, these figures imply that only 10-12% of EVs are charging at peak.

When the EV switches from charging (fully importing) to V2G (fully exporting) the swing in power is double the device's rating, eg an EV with a 7kw rating will have a step change of 14kW.

We can compare the potential large step from EV in 2035 to other potential sources of large steps, for example Hinkley C, which will have 2 reactors each of 1.6 GW. So, for example, at peak times for charging, if only 8% of the forecast 20GW load from EV chargers were to stop, that would result in a 1.6 GW load step, the same size step as a trip of a single Hinkley Reactor. Put another way that is less than 1%, just 225,000 chargers at 7kW, from the total 30,000,000 EVs expected on the road by the late 2030s.

A simultaneous change in a small proportion of EV chargers could impose a very large step change on the grid.

Unmanaged EVC Demand and V2G output for 2035, by FES Scenario.



Future Energy Scenarios, July 2021, National Grid ESO

Simultaneous action by a relatively small proportion of EVs charging could result unmanageable step loads on the grid.

POWER STEPS FROM EVC & V2G

Half-hour electricity market

In the GB electricity market, almost all energy is traded directly between those who produce it (generators) and those who consume it (mostly "suppliers" – so-called because they supply energy to the majority of consumers, including domestic customers).

Suppliers forecast their energy demand for each half hour into the future, and then agree contracts with generators to provide the energy. This can be up to a year or more into the future. Power exchanges enable both parties to fine-tune their positions up to 24 hours ahead (see opposite).

At one hour ahead of real time, generators and suppliers notify NGESO of their forecast power profiles, which determine their energy generation/consumption per half hour. They also submit prices for increasing and reducing their power level. NGESO checks that the grid can operate safely with the forecast patterns of generation and consumption and, if necessary, makes adjustments using the prices submitted. Further adjustments will be made if generation and demand are not balanced in real time. This process of adjustment is referred to as "system balancing", and the framework around this process is known as the Balancing Mechanism.

After real time, actual levels of generation or consumption of energy are checked for each user against their forecasts. If they don't match, the user is charged or refunded appropriately.

The smart metering system, at domestic consumer level, measures consumption at a half-hourly rate supporting billing systems for Time-of-Use tariffs for EV smart charging.

Epexspot

The half-hour interval is deeply embedded at all levels within the GB market design and operational practices.

POWER STEPS FROM EVC & V2G

Why half-hourly tariffs alone won't be enough

There is a small but growing population of loads (including EVs) who choose to use power on the cheapest rates, and switch on instantly at the start of a low-cost half hour; their impact can be seen at 00:00hrs and 00:30hrs in the graph on the right. Their behaviour is problematic, but still small enough to be manageable by NGESO.

At the other end of the scale, HVDC interconnectors would also like to change their transfer level instantly when prices change at the start of a settlement period, but this would be costly or impossible for NGESO to manage, and so ramp rate limits are applied to their output[1].

As the on/off switching behaviour of EVC loads continues as they scale up to GW levels then, as with interconnectors, these step changes in load at settlement period boundaries would become costly or impossible to handle. **To manage the future levels of EVC load, some new control mechanism is needed, which is more continuous than half-hourly ToU tariffs.** The need for a new control paradigm is reinforced by the Net-Zero ambition to match EV charging load to the availability of renewable energy[2], which changes minute by minute.

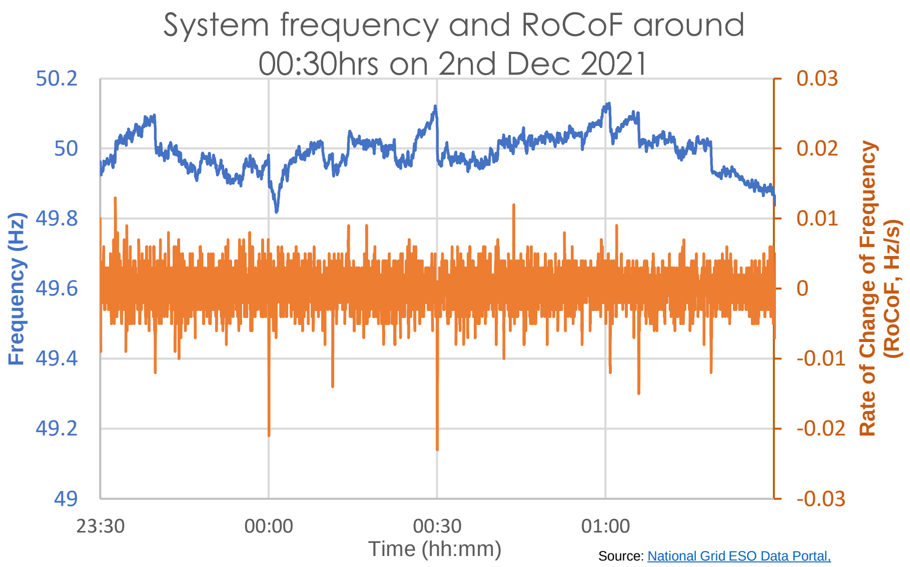
IRENA have highlighted the changing time granularity in electricity markets globally[3]. In the GB market, CoP 11[4] is a small but tangible sign of movement towards improved time granularity, as it allows for 5 minute interval. With shorter settlement periods there will still be discontinuities in the market price, but load step size should be reduced.

1). GC0154: Incorporation of interconnector ramping requirements into the Grid Code
2) "We'll be dispatching demand to meet the generation"
3) Increasing time granularity
4) Code of Practice (CoP) 11 document related to P375 'Settlement of Secondary BM Units using metering behind the site Boundary Point.

"Octopus Go. **Great value energy for EV drivers.** The smart tariff with super cheap electricity for 7.5p/kWh between 00:30 - 04:30 every night."

Note: Correlating between RoCoF step timing below and Octopus Go tariff does not demonstrate causation. This example is for illustrative purposes only.

https://octopus.energy/go/



Source: National Grid ESO Data Portal.

"Shortening dispatch/scheduling time intervals, the pricing of market time units and financial settlement periods would result in more granular imbalance prices, sharper signals and improved flexibility incentives"

Rethinking Electricity Markets

The half-hourly market has the potential to cause regular load steps. Without effective mitigation this could include multi-GW steps from EVC and V2G.

POWER STEPS FROM EVC & V2G

Increased step size: Coincident tripping

A special case of load steps is coincident tripping. Here, EVC or V2G responds coincident with another grid event. This can be more serious than a normal step or ramp as it increases the severity of an event, which increases the need for reserves. **Any coincident tripping is a concern as it risks generating a cascade event with ever-increasing tripping.**

Coincident tripping is typically caused by protection system operation. This is a well-known issues with DER, see GC0151[1] for examples on the GB grid.

Tripping may be at limits set by regulation
- Voltage
- Frequency
- RoCoF
- Phase imbalance

Other device protection may also cause tripping due to
- Loss of synchronism with the grid due to "PLL unlock" (Phase-Locked Loops (PLLs) are used by power converters to keep in step with the grid)
- DC current input
- AC over current
- User error/wrong settings

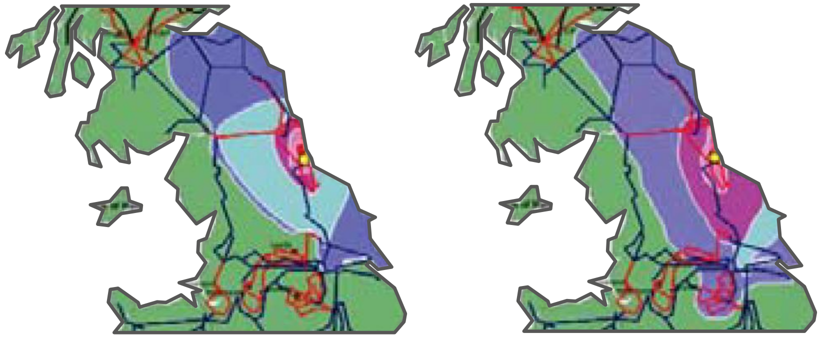
Coincident tripping can be fast enough to produce a step change in <10 seconds or may lead to a slower ramp change.

1). GC0151: Grid Code Compliance with Fault Ride Through Requirements

Impact of fault across 2023 network & 2033 network

Voltage drops to:

Fault Location
Less than 20%
Less than 50%
Less than 65%
Less than 75%
Less than 85%



Assessment of Fault Ride Through Requirement for Distributed Generators, National Grid

Current Data (Summer Min) | 2033/2034 Data (Summer Min)

The voltage dips are not only seen across the transmission network but they also penetrate down through the distribution system

Transmission faults can cause wide area, short duration, deep voltage dips, which may lead to coincident tripping of EV chargers or V2G. Longer duration voltage steps of up to +6% and -12% can occur at transmission level even for secured events.

These steps may trip EV chargers which were already operating close to the usual distribution system voltage limits of +10% and -6%. EV chargers are likely to trip well before tap changers operate to bring the LV voltage within the +10% -6% limits, which apply to a 10-minute average.

Table 6.5 Voltage Step Change Limits in Planning and Operational Timescales National Electricity Transmission System Security and Quality of Supply Standard
Assessment of Fault Ride Through Requirement for Distributed Generators , National Grid

Coincident tripping is not unique to EV/V2G, but the projected mass roll-out of EV charging could add to the risks posed by existing generation resources.

POWER STEPS FROM EVC & V2G

Examples and causes of coincident tripping

On May 9, 2021, the Texas Interconnection experienced a widespread reduction of over 1,100 MW of solar photovoltaic (PV) resources due to a normally cleared fault on the bulk power system. This event was analysed[1] in detail by NERC to identify the underlying causes.

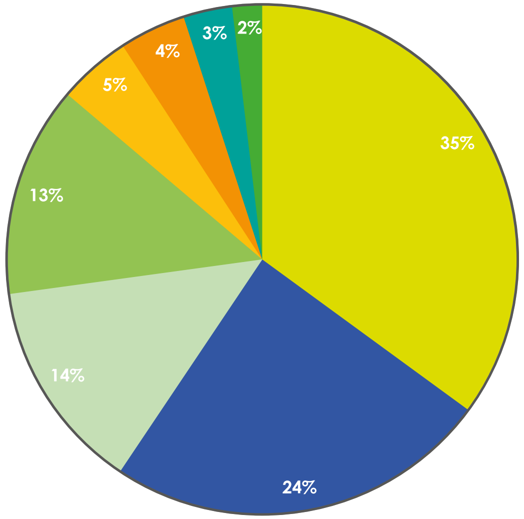
"An A-phase-to-ground fault occurred on a [Grid Step Up] transformer at a combined-cycle power plant during turbine startup for testing. The fault was caused by a failed surge arrestor. Protective relaying cleared the fault … in 3 cycles." This should have been the end of the incident.

The undesired coincident tripping event following the fault clearance involved solar PV facilities across a large geographic area of up to 200 miles away from the location of the initiating event.

Similar effects have been seen in Australia[2] and Europe[3] for relatively minor disturbances. **Many of the mechanisms for coincident tripping seen in PV may also be seen in future V2G systems as the inverter control algorithms have common design elements**. EV chargers may also respond adversely to grid transient events as they use similar software control for AC to DC power conversion.

1). Odessa Disturbance Report - NERC
2). Trip of multiple generators and lines in Central Queensland and associated under-frequency load shedding on 25 May 2021 AEMO
3). Factual Report on the Separation of the Continental Europe Synchronous Area on 24 July 2021

Causes of Coincident tripping of Solar PV



NERC Odessa Disturbance Report, September 2021

The Australian Energy Market Operator (AEMO) estimated that 5% (3-11%) of DPV inverters in South Australia disconnected (due to the action of the inverter) during a disturbance in May 2021. South Australia was remote from the original disturbance (in Queensland), and the power system conditions experienced in South Australia were relatively stable (voltage remained above 0.9 p.u, and frequency remained above 49.6 Hz).

Trip of multiple generators and lines in Central Queensland and associated under-frequency load shedding on 25 May 2021 October 2021 AEMO

Coincident tripping caused by renewable generation is acknowledged as a risk across global markets, with several examples in otherwise mature energy systems.

POWER STEPS FROM EVC & V2G

Delayed return after fault

Small generators subject to G99[1] are required to trip for a significant disturbance in voltage or frequency on the grid, or if they appear to have become disconnected from the grid. These generators are typically less than 50MW and include V2G.

Once normal grid conditions are restored, however, they are required to remain disconnected for a minimum of 20 seconds. For small amounts of generation, this safety measure will have little consequence, but as the volume of V2G grows, this risks amplifying the impact of what may already be a serious disturbance.

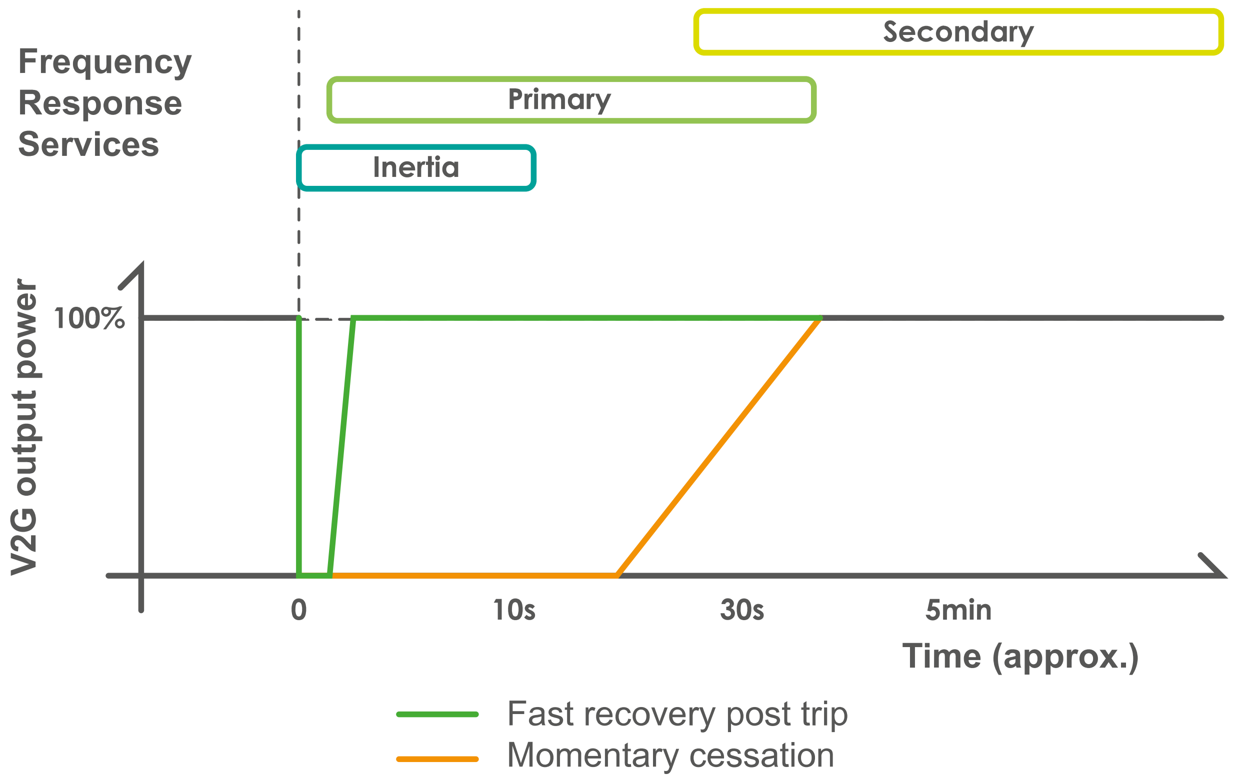
USA experience of PV tripping and delayed return after fault causing sustained power loss shows this to be a major concern as it leads to decreased generation output for an extended period of time[2]. **The delayed reconnection has been shown to increase the need for frequency response services and enhance the risk of cascade failure**. As shown in the example on the right, primary frequency response service is needed to cover the 20 second+ time period, rather than just inertia which is sufficient in fast recovering DER systems.

For some V2G solutions, delays may be much longer than the minimum 20 sec specified in G99. This may include:

- Software-controlled systems boot-up time
- Dependency on communication systems to re-enable V2G during restart

Some V2G devices could even default to charge while waiting for communication reconnection, further increasing system stress.

1) Engineering Recommendation G99 - ENA
2) Delayed return after fault is also known as Momentary cessation in USA analysis, also alternatively known as blocking.
Recommended Practices for Modeling Momentary Cessation NERC



There is an opportunity to refine standards to ensure that V2G maximises its potential to support the grid, instead of causing additional issues.

POWER STEPS FROM EVC & V2G

Increasing over-frequency risks

Historically under-frequency (<49.5 Hz) was seen as a far greater risk than over-frequency (>50.5 Hz). It has generally been easier to decrease generator output than suddenly increase it. Under-frequency has also been more of a focus because loss of generation was more common than loss of load, or outfeed.

Over-frequency risks are increasing. For example, the impact of the COVID crisis has shown[1] how unusually low demand increases over-frequency risk.

A trip of an interconnector exporting 1000MW may be the largest demand loss on the system. EV/V2G technology has some characteristics similar to interconnectors, in that it is converter-connected and (for V2G) supports bidirectional power flows. **Like interconnectors, converter-connected EV charging will present a risk of a large outfeed loss.**

Generation from V2G currently does little help to mitigate over-frequency risks. G99[2] over-frequency protection is set at 52Hz, well above the statutory 50.5 Hz threshold. Add to that, like smaller distributed generators, grid operators cannot directly control the output from V2G and have little if any real time visibility of its contribution which by 2035 may be 10GW or more.

“[Vector Shift]-only losses can’t cause outfeed losses, only infeed losses”
Whilst this may reflect the current situation, section 13 of the NGESO Frequency Risk and Control Report ("Future Considerations") also makes reference to new types of infeed and outfeed losses from nascent technologies. The projected growth in EVC and V2G, combined with the present lax regulation, would present such a risk.

Frequency Risk and Control Report, 2021, National Grid ESO

Example of level of risk on the system

#	Deviation	Duration	Likelihood
H1	50.5 > Hz	Any	1-in-1,100 years
L1	49.2 ≤ Hz < 49.5	Up to 60 seconds	2 times per year
L2	48.8 < Hz < 49.2	Any	1-in-22 years
L3	47.75 < Hz ≤ 48.8	Any	1-in-270 years

“Further investigation of high frequency deviations - **historically the focus has been on low frequency, but as more large outfeed losses connect this may need to change**”

Frequency Risk and Control Report, 2021, National Grid ESO

1). GC0147 Last Resort Connection of Embedded Generation
2) Engineering Recommendation G99 - ENA

Without interventions on standards, mass adoption of EV/V2G would lead to an additional risk of over-frequency from outfeed losses

POWER STEPS FROM EVC & V2G

EV smart charging step change mitigation

The risks of step change from EV charging systems are well known. Planned mandatory mitigations are being introduced for example via legislation, The Electric Vehicles (Smart Charge Points) Regulations 2021[1].

This mandates a default random delay of up to 10 minutes at the start or for any change in charging power. However, **the effectiveness of this mitigation is limited** because

- Consumers have the right to override this delay. (It is not immediately clear if a user-selected permanent or automated override of this delay may be legal.)
- The delay is not applied to all control mechanisms, for example timed charging controlled directly by the EV not the ChargePoint. The EV decreasing or stopping drawing power cannot be prevented by the ChargePoint.
- The choice of delay period was not based exclusively on analysis of grid operational requirements, it was based on estimates of consumer acceptance.
- It defines "peak hours" on weekdays as 8am to 11am and 4pm to 10pm. These times are fixed in legalisation and are likely to lead to ramp or step increases in demand at 11am and 10pm.
- In the event of loss of communication, the regulations allow default to immediate charge.
- Even with 10-minute randomisation, if 50% of EVs expecting to charge (based on FES 2021 assumptions) switch on at a given tariff point, this would generate a 10GW swing with a ramp rate of 1GW/min. This is well beyond interconnector ramping levels that are already problematic for grid operation

1). The Electric Vehicles (Smart Charge Points) Regulations 2021

"It is proposed to mandate that all smart CPs have a function that randomly delays how quickly it responds to a signal over a period. A randomised offset function has already been implemented by the Smart Metering Equipment Technical Specification – version 2 (SMETS2) and a similar approach has been adopted by the Publicly Available Specification 1878 (PAS) for smart appliances (including smart CPs). Consultation respondents largely supported introducing this requirement as it assists with grid stability, especially when recovering from power outages. **There were concerns expressed about that impact on consumer experience, therefore a maximum delay time of 10 minutes will be implemented as a default**, with the ability for consumers to override the delay if desired."

The Electric Vehicles (Smart Charge Points) Regulations 2021 Impact assessment

"This requirement contributes towards the objective of grid stability. If many consumers have similar incentives to smart charge (for example a time of use electricity tariff that offers cheaper rates after 12am) then there could be a sudden spikes in power draw from the grid at these times. The randomised delay function proposes to **partially address this** by staggering the response across CPs."

The Electric Vehicles (Smart Charge Points) Regulations 2021 Impact assessment

Additional thinking is required to ensure that markets and standards tackle a range of expected behaviours of coordinated EV/V2G

POWER STEPS FROM EVC & V2G

Step change due to unintended consequence of regulations

Regulatory requirements introduced for new classes of generation or load may promote instability, especially as adoption increases. This has been seen, for example, in the fixed on/off thresholds for PV over-frequency response in Germany at 50.2Hz. See orange box right.

There are plans to update G99[1] to introduce a mandatory frequency response for storage devices, such as EVC/V2G. This has the potential to provide a very large stabilizing resource for the GB grid at no ongoing cost.

However, due to the scale of EV charging load, the regulations need to be very carefully written to avoid unintended consequences. For example, if a software engineer wanted a simple implementation for the regulation shown in G99 figure 12.2 they could use

- EV chargers stop charging < 49.5Hz.
- V2G-capable chargers generate 1 PU (100%)< 49.0Hz

This is illustrated by the red arrows overlaid on Figure 12.2.

This has the potential to introduce two 10GW+ steps as frequency decreases, which is significantly larger than the balancing power available from other resources. The rapid change of power flow also risks LV network over-voltage.

1) Engineering Recommendation G99 - ENA

"According to the interface protection rules of that time an immediate shut-down of the PV inverter was required if the grid frequency should at any point in time reach or exceed 50.2 Hz. In itself this is an appropriate rule to prevent over generation until the grid's primary control systems have had time to recover the situation.

Considering that the combined power contribution from the numerous PV inverters have reached proportions of several gigawatts, especially during high production periods, the implementation of this interface protection rule at a fixed 50.2 Hz, **unwittingly instigated an instantaneous loss of generation that can be significantly larger than the balancing power available Europe-wide for primary frequency control, rendering the overall system unstable**."

The German 50.2 Hz problem

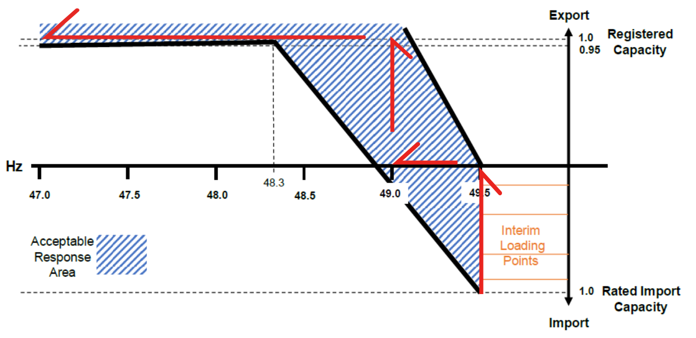


Figure 12.2 Change in Active Power of Electricity Storage Device with falling frequency (not to scale)

Red arrows show a permitted, but undesirable implementation of the requirements, shown in figure 12.2 of G99[2], for power change with falling frequency.

2). Engineering Recommendation G99 - ENA

Standards can introduce unintended negative consequences for grid stability, especially when a new technology is adopted rapidly.

RAMP RATES

Why include ramps in Project REV?

Project REV scope was defined as covering the period 1 cycle to 10 seconds. As part of the analysis to date we have identified that some of the issues with rapid changes in load or V2G will have effects outside this range, often in the range 10 seconds to a few minutes. We have decided to include these in the analysis as high ramp rates have a major impact on grid operability and could be as great a threat as steps.

EV-related ramps may be caused by:-

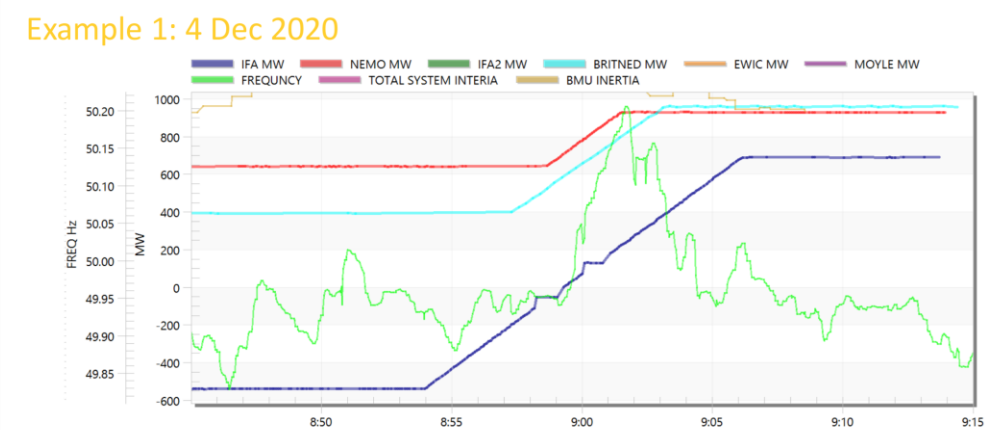
- Normal operation of smart charging control systems.
- Failure of smart charging control or communication systems, equipment failure or cyber attack
- Direct human control of charging systems. We considered that this was unlikely to produce a step but could produce a significant ramp.

Recent concerns have been raised by NGESO regarding potential ramp rates from interconnectors and it has been highlighted[1] that existing arrangements will not remain viable. When designing smart charging systems and regulations, the impact of ramps on the grid needs to be understood and managed.

Fast ramping of EV charging could leave the grid out of balance if generation is unable to match the ramp in demand.

1). GC0154: Incorporation of interconnector ramping requirements into the Grid Code

"Why are we looking at interconnector ramping now?
Operational Drivers - The control room already face operational challenges from the current IC ramping arrangements. With an increased number of ICs coming onto the network (5 continental IC by 2022) current IC ramping arrangements will not remain viable (potential full swing of over 12GW at a rate of change of 500MW/min). This would significantly influence the services needed to manage the system."



Incorporation of SOGL Article 119 and ramping requirements into the Grid Code GCDF May 2021

nationalgridESO

- 3 interconnectors ramp simultaneously
- Total flow of change ~ 2050MW
- Max ramp rate of 275MW/min
- Frequency moved just outside operational limits

A range of "normal" and fault conditions may drive rapid load or generation ramps from EV/V2G beyond the capability of existing services.

SYGENSYS

RAMP RATES

Existing ramps & the potential from EVs

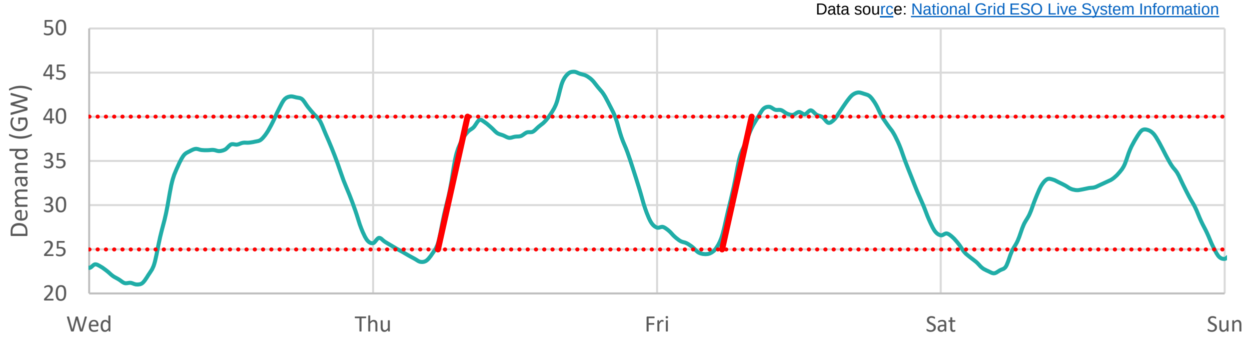
The grid control room, known as the Electricity National Control Centre (ENCC), has to manage the balance between supply and demand during ramps. This includes regular events such as the morning pickup and other anticipated events such as TV pickups. The morning pickup can be around 15GW between 6am and 9am, with a peak ramp-rate on some days of up to 10GW/hr, whilst a TV pickup can, on occasion, be 1GW over a matter of minutes.

In the 2030s, EV charging and V2G will have a potential swing of over 30GW (even after allowing for diversity effects), far exceeding the change possible from interconnectors. Smart control systems must be designed such that ramp rates are maintained with manageable limits for the control room, and designed such that they help reduce rather than increase system operational costs. This must be achieved during normal operation and during fault conditions.

Well-implemented smart charging control has the potential to reduce ramp rates. However, **poor implementation or failure of smart EV control systems could lead to excessive ramp rates which would destabilise the grid.**

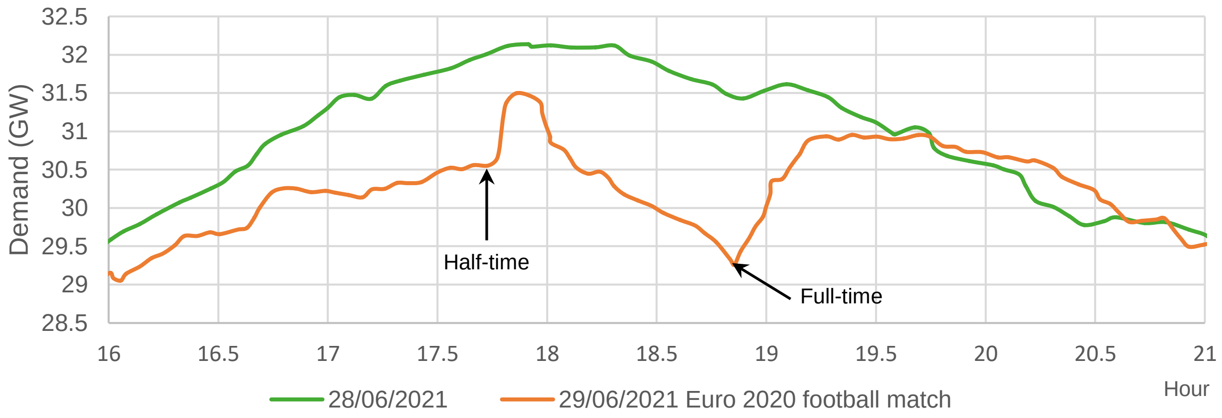
Daily demand variation highlighting weekday morning ramps. November 2021

Data source: National Grid ESO Live System Information



Euro 2020 TV pickup

National Grid ESO blog



With smart charging systems, the potential load changes are both large in size and fast, resulting in much larger ramp rates than have been seen historically.

RAMP RATES

Ramps remaining after step change mitigation

The Electric Vehicles (Smart Charge Points) Regulations 2021[1] introduced a random delay in the control system for smart charging with a default value of up to 10 minutes. This aims to prevent step changes, however it leaves open the potential for fast ramp changes.

FES 2021 suggests a diversified but unmanaged (non-smart) peak charging demand of 20GW in some scenarios. If all these EVs seek to exploit the start of a cheap tariff period, then even excluding the impact of reversal of V2G, with 10-minute randomisation this would result in a 2GW/min ramp lasting for 10 minutes. That is far beyond what can currently be managed, and even this only represents about 10% of the total population of EVs on the network.

A random delay mechanism of this type can help avoid fast loads steps, but is not sufficient to prevent unmanageable load ramps. All aspects of the design of smart charging control systems must be designed to minimise the risk of excessive ramp rates.

Grid stability is rightly on the British Standards Institute (BSI) list of the principles critical for effective DSR which are being used to help drive future regulation and standardisation.

1). Electric Vehicles (Smart Charge Points) Regulations 2021

"Following a public consultation, BEIS outlined four policy principles seen as critical for effective DSR through ESAs:

• Grid stability: the prevention of outages on the grid caused by erroneous or simultaneous operation of ESAs.
• Cyber security: the prevention of unauthorized access to ESAs by third parties.
• Interoperability: the ability of ESAs to work seamlessly across any DSR service operated by any system player.
• Data privacy: the secure storing of data on the device or with any controlling party."

BSI Energy Smart Appliance Program

More advanced ramp mitigation interventions may be required across standards and market design.

RAMP RATES

Smart charging ramp triggered by an external event

In this world of fast communication and automated responses to news, an item about a storm or shortage of supply could lead to a ramp in demand.

Publicity could produce a mass response from EV owners wanting to charge ahead of potential supply problems. This could, for example, be in response to a weather warning.

An automated response to an external event such as a weather forecast, or even an ESO margin notice, could lead to a significant increase in demand. An aggregator's system, controlling a large number of chargers, could respond within seconds to a few minutes.

Slower consumer response over hours may include some users overriding their smart charging controls by operating the "charge now" or "boost" function. Given current and proposed regulation, this function bypasses most smart charging management mechanisms designed to help protect the grid from ramps and overloads.

These types of event are a form of the familiar "panic buying" seen for commodities ranging from petrol to toilet tissue.

Electricity Capacity Market Notice Currently Active

Posted by National Grid Electricity System Operator at 1:04pm on Friday 3rd December 2021

Commencement time of notice	5:30pm on Friday 3rd December 2021
Circumstances that triggered notice	Margin below threshold set out in Capacity Market Rules
Transmission Demand and Operating Margin (MW)	42,518
Aggregate Capacity of BM Units expected (MW)	42,472
Additional Capacity (MW)	No definitive information regarding additional capacity is currently available to the Electricity System Operator.

4 Hours 26 minutes warning of low electricity supply margin

GB Electricity Capacity Market Notices

4 Hours 4 minutes warning of high risk of storm damage

Rare red weather warning issued for Storm Arwen

Rare red weather warning issued for Storm Arwen

Author: Press Office
10:56 (UTC) on Fri 26 Nov 2021

The Met Office has issued a rare red weather warning for coastal areas in the northeast of the UK as Storm Arwen will bring high winds and disruption for much of the UK.

A rare red weather warning for wind has been added to existing amber and yellow wind warnings, with coastal areas on the east coast of Scotland and the northeast of England set to see the most disruptive winds, with gusts expected in excess of 80mph.

The red warning will come into force from 15:00 Friday and will last until 02:00 Saturday morning.

Smart loads such as EVs will be subject to aggregator decisions, based on external data sources, that may introduce rapid ramp rates.

RAMP RATES

Smart charging system failure

Ramps may occur if, for example, communication networks are disrupted by failure or congestion.

More generally, wide-area disruption impacting many EVCs could originate from several possible sources, including:

- Internet service provider
- Cellular network
- Cloud services provider
- ANM systems
- Aggregator's system
- Failed software update

In all cases, it is likely that smart charging operation could be quickly disrupted. **With a loss of smart charging functionality, current EV charger designs will generally fall back to unmanaged charging and attempt to fully charge the EV battery.** This could lead to an increase in demand at national level and potentially overloads at local level. The latter is especially likely if these EVCs were participating in constraint management.

The behaviour of EVCs under these conditions could be described as "Event Ride-Through" (as distinct from "Fault Ride-Through", which is concerned with response to faults on the electricity grid). Designing communication and control systems to provide good event ride-though characteristics, from both consumer and system operator perspectives, will be important as EVC capacity increases to tens of GW.

"Nest thermostat owners out in the cold after software update cockup. Buggy code blamed for drained batteries, failed heating."

The Register 14 Jan 2016

"Data from comparison and switching service Uswitch.com has revealed that nearly 15 million UK consumers have suffered broadband outages lasting three hours or more in the past year"

Computer Weekly 27 Jul 2021

Amazon Web Services is back online following a two-hour-outage that also took out Netflix, Doordash, Hulu and Twitch for tens of thousands across the globe.

Mail Online 15 December 2021

Smart charging is a system of many interconnected components, any of which may fail. The design of fall-back operation must consider the impact on the grid.

GRID STABILITY

Under-voltage cascade and fault-induced delayed voltage recovery

EV chargers will typically operate at constant power or, if they reach a supply current limit, at constant current. Constant current operation offers less load relief than traditional resistive loads; power demand falls linearly with voltage, compared to falling with voltage squared for resistive loads. In constant power operation there is no load relief and current will actually increase as voltage falls.

This impacts the voltage stability curve and increases the risk of voltage collapse on the grid. For some voltage sags, common EV chargers may remain charging to voltages as low as 70% of nominal supply voltage or, in the case of universal mains versions, as low as 40%.

If voltage falls to 80% or lower during a fault, existing regulation requires that generation governed by G99, such as domestic PV and V2G, disconnects after 2.5 seconds and remains disconnected for at least 20 seconds. There is therefore a risk that PV and V2G generation trips before EV charging load disconnects, increasing further the risk of voltage collapse.

As voltage starts to recover, EV charging may reconnect before embedded generation, delaying further recovery. This is known as Fault-Induced Delayed Voltage Recovery (FIDVR) and has been seen in the US grid[1] with high penetration of PV generation and air conditioning loads.

1). Fault Induced Delayed Voltage Recovery (FIDVR): Modeling and Guidelines

"As expected, the load composition considerably affected voltage stability. Simulations conducted with loads modeled as pure "constant impedance" showed the largest resilience to voltage stability problems, as the loads exhibited an inherent "natural" unloading characteristic. On the other hand, simulations performed with loads modeled as pure "constant power" resulted in considerably unfavorable conditions, both in terms of active and reactive power. **It is therefore of great importance to dispose with reliable load models, since over or under estimation of a certain load-type component can result in too optimistic or too pessimistic power system operation limits."**

Enhanced Contingency Analysis—A Power System Operator Tool

V2G like solar PV generation could worsen the effects of FIDVR events because present standards do not allow inverters to ride-through some voltage and frequency events.

Fault Induced Delayed Voltage Recovery (FIDVR) Indicators

EV charging does not provide the same load relief as historic loads; this would impact stability on transmission and distribution grids.

GRID STABILITY

System fault ride-through

The fault ride-through performance of smart EVC systems is complex as it may involve the combined effect of many elements. As an example, we analysed one specific smart charging equipment combination:

- Electric vehicle on-board-charger-module (EV OBCM)
- Charge point (EVSE)
- Communication hub
- Broadband access point

The following were shown to cause the EVC system to stop charging:

- Voltage swell of over + 12% for more than 5 seconds
- Voltage sag to under - 12% for more than 5 seconds
- A supply interruption for 0.1 seconds

In all cases a manual reset is required before charging restart. This shows a potential for loss of load coincident with a power quality event. After a power outage, recovery time for smart charging communication was approaching 3 minutes.

This particular example should not be taken as a typical representation of smart charging system. It was a one-off analysis used to indicate the complexity of fault ride-through and recovery. Other systems could have radically different performance.

Key findings from EV charger analysis and testing

- EVSE under and over-voltage thresholds are specified at 230v +/-12% with 5 sec delay, a manual reset is required. Testing confirmed that performance.
- A sag (swell) to the EVSE of 230v -40% (+17%) for 4 seconds did not cause a trip.
- A supply interruption for 0.1 sec causes EVSE to produce an error message either related to loss of protective earth to vehicle or loss of power output to vehicle. Both require a manual reset.
- OBCM operated 230v -20% to +13% without tripping (beyond the ESVE limits).
- Communication hub operates from 33v to >270v and has a recovery time, after power outage, of about 20 seconds.
- Broadband access point operates from 55v to >270v and has a recovery time, after power outage, of about 150 seconds

Poor fault ride-through from EV charging and V2G could lead to large scale coincident tripping of load or generation.

GRID STABILITY

The impact of EVC on load response

Historically as grid frequency or voltage falls, the power consumed by loads falls. This has been a natural characteristic of loads such as resistive heaters and incandescent lights whose power consumption varies with voltage, and motor loads whose power consumption varies with frequency. This phenomenon, called load relief, helps stabilize the system. In addition to this, synchronous motors have inertia which further aids system stability. Loads are estimated to provide approximately 20% of GB grid inertia[1].

Existing EV chargers have different characteristics:

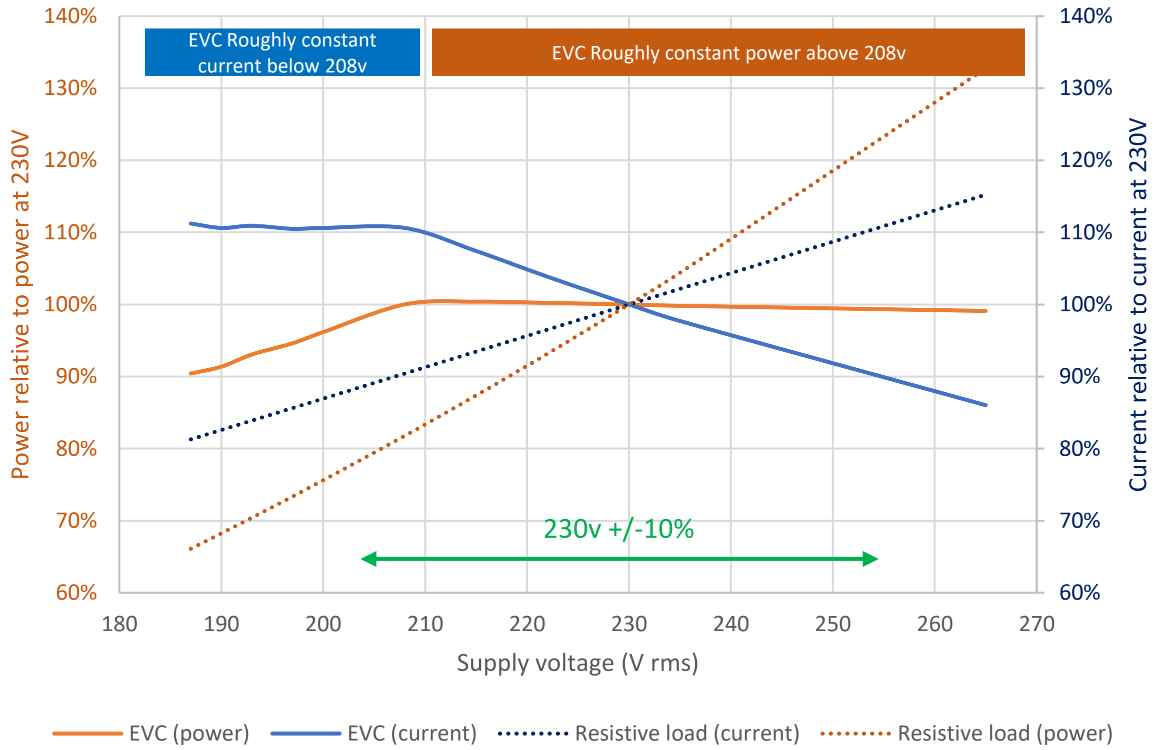
- Limited or zero voltage load relief: Largely constant power or constant current in the voltage range 230V +/-10%.
- Under and over-voltage protection may cause tripping for wide voltage variations.
- No frequency load relief: Little if any variation of power with frequency in the range 45 to 55 Hz;
- No natural inertia.

As the scale of EV charging and V2G increases, the impact on system-wide load response will affect the dynamics of the transmission and distribution systems, reducing voltage and frequency stability[2]. Composite load models used for grid stability analysis will need to evolve to match the changing load.

1). Demand Side Contributions for System Inertia in the GB Power System

2) The Impact of Power-Electronics-Based Load

Example EV charger constant power/constant current for varying supply voltage compared to a resistive load



EV charging load will reduce load relief leading to reduced voltage and frequency stability.

GRID STABILITY

The impact of EV charging on SSO risk

Load relief is a form of system damping. This damping reduces with increasing numbers of power-converter-connected loads, so there is an increased risk of system oscillation including Sub-Synchronous Oscillation (SSO).

EV chargers use active power electronics to control their consumption and generation of power (for V2G). These electronic control systems have similarities with control characteristics found in other power converters including HVDC links. This gives rise to an increased risk of new or enhanced Sub-Synchronous Oscillation (SSO) modes.

The risk of new SSO modes arising from series compensation and power electronic converters for generation and HVDC links was identified by the VISOR project[1], and this risk appeared to materialize on 24th August 2021; see opposite.

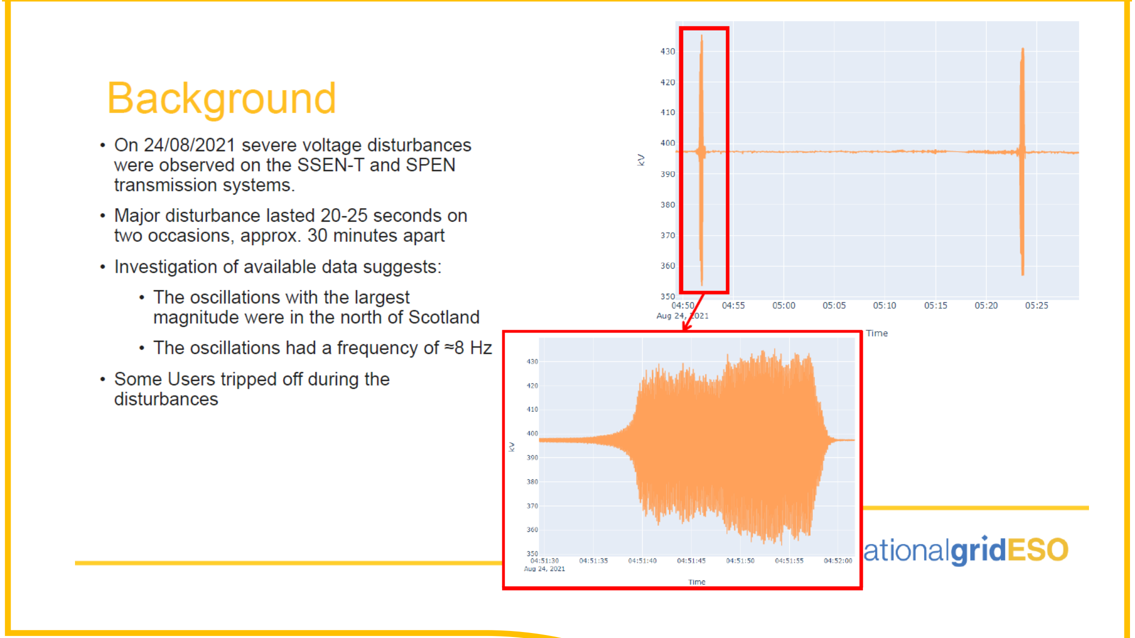
The impact on stability of aggregated power and load from new resources, such as V2G and EVC, cannot be ignored. For example, the risk of converter-connected PV resources contributing to Sub-Synchronous Torsional Interaction (SSTI) have also been highlighted by research[2].

1) VISOR project

2) Impact of Aggregated PV on Subsynchronous Torsional Interaction

"**Sub-Synchronous Oscillation (SSO)**
The increasing use of series compensation and power electronic converters associated with renewable generation and HVDC links add vital flexibility and capacity to the power system and help in the move to a low carbon future. However, these control devices introduce new challenges, in particular, the potential for SSO…"

VISOR project



G-PST/ESIG Webinar Series:
Research Agenda for Transformed Power Systems

Power converter-based resources may provide no load relief so can enhance the risks of SSO and introduce new modes.

SYGENSYS

GRID STABILITY

Over-voltage cascade

Resistive heaters and synchronous motors will naturally survive brief over-voltages, so historically few loads have included Over-Voltage Lock-Out (OVLO).

Many new types of high-power loads, including EV charging, are being connected to the grid by power converter technology. The semiconductor devices used with these products are more sensitive to damage by over-voltage so will generally include the fastest-acting over-voltage protection which is allowed by regulation.

Regulation allows over-voltage tripping of EV charger loads above 110%. This may occur before G99 embedded generation trips at 114%.

If an event on the transmission system causes an ongoing increase in voltage (for example, tripping of a 400kV voltage control device), the rise in voltage could trip some EV charging load, leading to a further voltage rise and potentially further EV charger tripping. GB LV voltages are commonly above nominal (e.g. 240V on a nominal 230V system), which increases the risk.

EV charging therefore leads to the potential for an over-voltage cascade event with a large amount of load disconnecting, possibly resulting in a system-wide over-frequency as well as regional over-voltages. (Note that an increase in system frequency will also cause voltages to rise due to an increase in reactive power generated by shunt susceptance). Load reconnection after this type of event could be slow as some EV chargers require a manual reset after over-voltage.

One major impact of distributed solar generation on the network is voltage rise – having voltage exceeding the limit at certain nodes. This undesirable phenomenon is more severe at higher solar penetration levels and during the low demand times. It is a well-known challenge to distribution network operators (DNOs); the UK Power Networks reported a voltage rise of more than 2% in some feeders in 2015 due to residential PV installations.

Solar Integration in the UK and India: Technical barriers and future directions

Survey of typical GB supply voltage

"Points were associated mainly with domestic consumers, with some businesses also included, and captured single-phase voltage measurements at or electrically very close to the supply terminals for a period of at least one year (10-minute averages) **The most common recorded voltages lay between +5% and +8% of the nominal 230V"**

Project NETWORK EQUILIBRIUM: Voltage Limits Assessment Discussion Paper

It is important to consider that loss of load from EV charging could lead to an over-voltage/over-frequency cascade event.

GRID STABILITY

Stability during low power demand

As the amount of embedded generation increases, local demand may at times be matched by local supply. One example of active matching of local supply and demand comes from the combination of smart charging EV and onsite PV: the EV load can automatically track the PV output to achieve zero net export. This is beneficial where export tariffs are lower than import tariffs.

Over wider areas, local energy cooperatives and peer to peer trading can have similar effects. This may contribute to periods of low demand seen at transmission level.

Managing system stability at periods of low demand can be challenging. This is especially the case if many of the embedded generation resources are not frequency sensitive, not dispatchable by the system operator and may not include reactive power control capability or Power System Stabilizers (PSS). Introducing new features into EV chargers and V2G control could turn this challenge into an opportunity.

"Our Future Energy Scenarios suggest that, by the 2030s and 2040s, reduced demand periods will be much more frequent – likely to be the normal state of affairs in Summer and quite usual in Spring and Autumn."

The challenges posed by COVID-19 and the lessons learned

"Instead of procuring more and more inertia, we could somehow replace it with a fast power injection from new technologies such as battery storage. That's the kind of future where we would deal with stability in a smarter way with more renewables, rather than turning on gas plants."

Lockdown lessons could enable energy system shake up

EV charging could provide a useful tool to manage stability during low demand, combining V2G with robust standards and market design changes.

GRID STABILITY

Low inertia, high RoCoF and low fault infeed

Increasing use of renewable generation is leading to a fall in grid inertia. EV systems will continue this trend as there is no inherent inertia from EV loads and V2G does not provide inertia.

Lowering inertia leads to higher Rate of Change of Frequency (RoCoF) for the same loss of infeed or outfeed. This means there is less time to arrest the change in frequency before control limits are exceeded. Implementation of RoCoF tripping in V2G systems, as a means of Loss of Mains protection, is a potential cause of coincident tripping, but limits have been revised[1] to 1Hz/sec to reduce the risk.

The lower fault infeed from inverter-connected generation, including V2G, also leads to a greater risk of large phase jumps. This can impact the PLL in V2G and EV chargers with the potential to cause them to disconnect. The latter is of particular concern for high frequency events, for example where a transmission fault causes the loss of an exporting interconnector.

With the growth of inverter-connected generation in place of synchronous machines, the management of inertia is becoming part of normal grid operations[2]. Grid operating policies have been updated to help reduce balancing costs, but this may increase the incidence of larger frequency excursions.

1). ALoMCP programme
2) System Needs and Services for Systems with High IBR Penetration

Future grids dominated by renewables and lacking inertia will have very fast dynamics, as compared to the past grids dominated by large thermal generators. This is both a challenge and an opportunity: **changes will happen much faster, but we also have the chance to react to them much more quickly.**

Implementation of FRCR 2021

Phase 1 includes "Removing the tighter frequency limit of 49.5Hz for smaller infeed losses - only applying the wider limit of **49.2Hz for up to 60 seconds** to all BMU-only infeed losses."

See slides in SQSS Panel papers, December 2021:
SQSS Panel Headline Report – 13 December 2021

Like other inverter-connected generation or storage, EV/V2G will not naturally provide inertia, with the associated challenges in managing RoCoF.

GRID STABILITY

Grid-forming inverters

Currently some Inverter-Based Resources (IBR) may provide fast frequency response supporting the NGESO Dynamic Containment[1] service. This specifies full delivery of response within 1s (but no faster than 0.5s).

In future, IBR will be able to provide inertia-like services ("synthetic inertia"). These systems are known as grid-forming inverters, ("GFM") in contrast with existing grid-following inverters ("GFL").

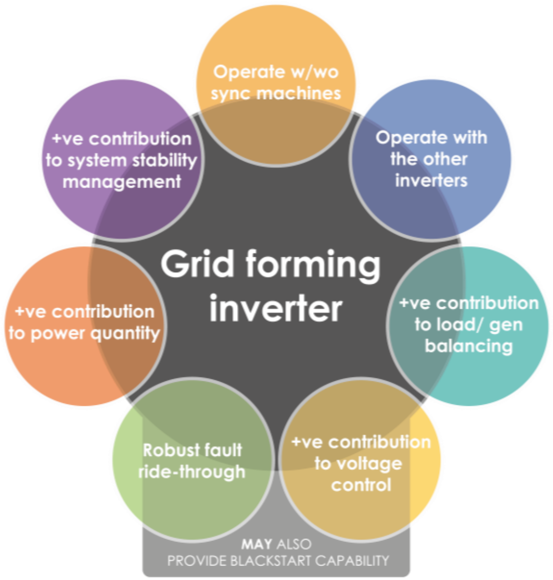
NGESO have released the Minimum Specification Required for Provision of GB Grid Forming Capability (Grid Code modification GC0137[2]), which defines the required response time:-

"Grid Forming Plant that starts to respond naturally, within less than 5 ms and can have frequency components of over 1000 Hz."

This sub-cycle response time will provide current injection in response to RoCoF, phase jumps, harmonics and voltage transients. **This emulates the inertia characteristics of synchronous machines, allowing grid-forming inverters to support short-term stability and help maintain power quality.**

Future V2G implementation will provide storage with the potential of grid-forming capability and multi-GW capacity, thus V2G has the capability to provide advanced stability services.

1) Dynamic Containment
2) GC0137: Minimum Specification Required for Provision of GB Grid Forming (GBGF) Capability

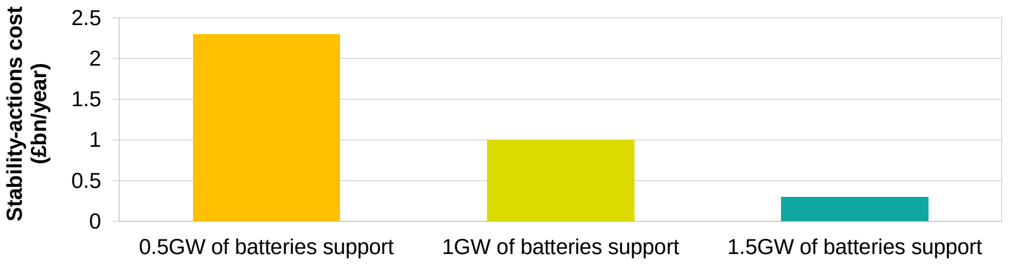


What does it mean to be Grid Forming?

- "GFM inverter can be defined based on its capability and the grid services it provides"
- "These services should be provided while *meeting standard acceptable metrics* associated with reliability, security, and stability of the power system and *within equipment limits*."

Grid Forming Inverters: EPRI Tutorial

Projected costs for stability actions in Great Britain grid by 2030, as a function of the capacity of batteries providing stability support to the grid.



World economic forum blog post

Grid-forming technology applied to IBRs, including V2G, has the potential to help address falling inertia.

GRID STABILITY

Stable islands

Grid-Forming IBRs should help to improve system stability, however their deployment may have some unexpected consequences.

Usually, small islands formed during grid fault conditions are unstable: supply and demand are not matched and there is little if any inertia to help short-term stability. Wide voltage and frequency excursions will trigger Loss of Mains protection on all generators, causing the island to lose power. This has traditionally been regarded as a safe outcome, since it ensures that field staff working to restore supplies are not at risk from unknown live systems.

Grid-forming controls on V2G and other inverter-based resources will provide synthetic inertia, substantially increasing the possibility of stable islands forming. These temporarily isolated microgrids may improve supply resilience for consumers but could add considerable complexity to the management of system disruption in future: Distribution control rooms may need to be aware of these islands to ensure the safety of field staff, and to use whatever dispatch tools are available to manage conditions in the islands.

Large-scale adoption of frequency or voltage-based droop controls in Demand Side Response systems, including EV charging, would also increase the possibility of stable islands forming.

"[EirGrid & SONI] acknowledge that in cases where load and generation are balanced in an island, it is already difficult to provide adequate loss-of-mains protection. In general protection employed on the distribution networks includes under- and over-frequency elements, and under- and over-voltage elements, as well as loss-of-mains protection. Work is required to understand and determine the appropriate settings throughout the distribution protection schemes that can adequately detect loss-of-mains in balanced islands."

RoCoF Modification Proposal– TSOs' Recommendations

"A microgrid is an integrated energy system consisting of energy generation sources, storage options, and energy users. It can be connected to the main electrical grid or may operate in isolation, as an 'island', often in rural environments.

Those microgrids connected to the main grid can also disconnect and operate independently if necessary, i.e. if there's a fault within the main grid."

Multi-energy "island" Microgrids can increase grid resilience

Stable island formation represents both an opportunity and a threat; either way, new protection or control systems may be required.

GRID STABILITY

Competing EV smart charging control systems

Many control systems and organizations may exercise control over EV chargers. For example, a single EV may be controlled by all of the following:

- Direct control of the EVSE by the vehicle owner
- EV control by the vehicle owner via the EV manufacturer's app
- Local control on-site system by a Home Energy Management System (HEMS)
- Control by an aggregator in response to ESO and an energy company's needs
- DSO ANM control via the smart meter system communication system

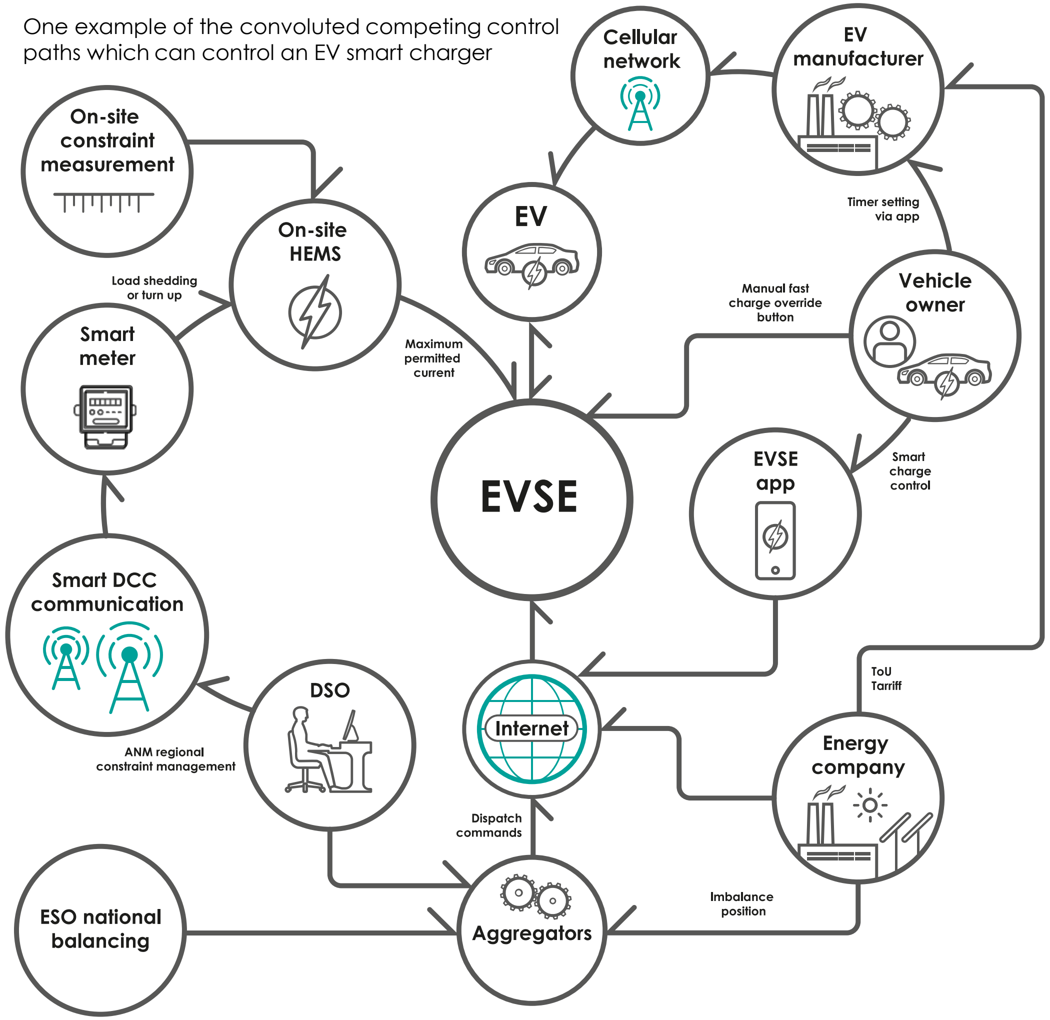
Each of systems will have different goals which may include:

- Vehicle driver needs
- Physical system constraints (current limits etc.)
- Financial objectives
- Regulatory obligations

Two or more competing systems risk producing oscillatory modes or other forms of instability. These could range from repeated start-stop charging for an individual EV, to wide-area high-power oscillations at GW level, or even cascade events. Multiple communication channels, control loops with delays and re-try mechanisms could all provide paths for instability.

Analysis of these scenarios is complex, especially when system design and market regulations are evolving rapidly, algorithms may be proprietary, communications may become congested or unreliable, and major changes can occur between pre- and post-fault conditions.

One example of the convoluted competing control paths which can control an EV smart charger



It is easy to focus on one narrow aspect of smart charging and miss the potential of competition for control of each EVC.

GRID STABILITY

Primacy of smart charging control

As DSR plays an increasing role in managing constraints and minimizing grid balancing costs, it will become a critical part of national infrastructure. Maloperation, for example due to conflicting control signals, could have serious impacts with risk of failure to deliver expected services potentially leading to system instability.

This challenge is acknowledged by the industry and mechanisms enabling service stacking and prioritizing of service provision to DSOs and ESO are being developed.

Behind-the-meter DSR assets, such as EV chargers and V2G, add another level of complexity as they may be part of a local HEMS. HEMS optimisation goals such as zero export from PV may conflict with DSR controls to an EV charger.

It is important that primacy of control is understood by both consumers and grid operators. This needs to include normal day-to-day operation and operation during fault conditions, such as loss of DSR communication, and in exceptional circumstances such as demand management at time of shortage of supply.

"As we reform our own balancing services, we want to make sure that stacking is possible, where feasible, across DSO and ESO products." (NGESO)

Enabling the Distribution System Operation (DSO) transition

"Due to the increasing coupling between the TN and DN, the transmission system operators (TSO) and distribution system operators (DSO) have to be properly coordinated for effective voltage regulation on both sides. This will be a major challenge as reactive power sources connected to the TN are replaced by DER in the DN, and will require more active participation of DNs on voltage support of TNs" (IEEE PES Task Force)

Review of Challenges and Research Opportunities for Voltage Control in Smart Grids

"Conflict of service can occur during periods of time where the needs of the transmission system operator and the distribution system operator do not align. In addition, the action of automated control systems can also cause a conflict where select parties have their output automatically adjusted, in isolation of services required to manage wider transmission and distribution system needs." (Electricity Networks Association)

Open Networks Proejct: Operational DER visibility and monitoring

"Some Texans who opted in to energy-saving plan didn't realize what they agreed to."

arsTECHNICA 21 June 2021

Grid operators: Do you know if someone or something could override your control of DSR when you need it most?

GRID STABILITY

Real-time smart charging observability and data for post-event forensics

In the 2030s, with over 10GW of load or generation attributed to EVs, there is potential for these LV-connected devices to have a significant impact at transmission level.

EV and V2G control systems could display undesirable behaviour (steps, ramps or oscillatory power swings) for a number of different reasons:

- a flawed software update released by an EV manufacturer or aggregator;
- control algorithm issues;
- reduced quality of service from a cloud service provider;
- conflicting signals to a group of assets from DNOs and ESO;
- malicious action.

Because of the highly distributed nature of these assets and the traditional sparsity of real-time metering on the LV system, a system incident arising from EVs would be almost impossible to diagnose.

Even if EVs can be identified as the cause of an incident, there will still be the considerable challenge of diagnosing the cause amongst the multiple control systems and parties involved. Not all parties may be subject to Ofgem regulations encouraging disclosure, and not all may share the collaborative mindset of traditional industry participants (seen, for example, in the August 2019 incident investigation).

Some mechanisms do already exist to access post-event data, while addressing consumer privacy and market sensitivities, but these are neither comprehensive nor timely. A capability for post-event analysis is one key purpose for data gathering within future energy data systems[1].

1). Energy Data Taskforce

"Today, data quality is often poor, information can be inaccurate, imprecise or missing. Data gaps may exist for a number of reasons:

- It may exist in a non-digital format
- It may be collected and used for a specific purpose but not stored
- It may not have been collected

Data gaps restrict the deployment of new operating models, limit innovation and maintain the status quo." (Energy Systems Catapult)

A strategy for a Modern Digitized Energy System

"To assess the response of DPV to the disturbance, AEMO procured anonymised 60-second and 5-second resolution generation data from Solar Analytics for a sample of 24,257 DPV inverters (all systems smaller than 100 kilowatts [kW]). To cross-check these findings and confirm the methodology applied, AEMO also collaborated with Tesla to analyse anonymised data from its fleet of a comparable number of DPV systems (installed at customer sites associated with Tesla Powerwall systems)."

Trip of multiple generators and lines in Central Queensland and associated under-frequency load shedding on 25 May 2021

We need good data on smart charging operation to be able to answer the questions "What is happening now?" and, post-event, "Why did it go wrong?"

RESTORATION

Restoration (previously "Black Start")

Black start[1], now referred to as Restoration by NGESO, is the process of recovery from an outage affecting all or a section of the grid from generation resources not connected to any part of the grid which has power. It involves the sequential reconnection of generation and demand, always maintaining operation within safe limits, until all parties are back on supply.

Restoration is a very rare situation for the GB grid due to the high levels of reliability achieved. It is a challenging process which cannot be practiced at a national scale, other than by simulation exercises.

EV charging and V2G could significantly impact the restoration process. If smart charging systems are poorly designed, implemented or maintained, restoration could become far more challenging.

Conversely, EVC and V2G have the potential to provide a new mechanism to help balance supply and demand during restoration. The Distributed Restart project[2] is paving the way for distributed energy resources to provide this kind of service.

1). Restoration Services - NGESO
2) Distributed Restart

Black start: the most important back up plan you've never heard of

"In October 1987, there was a regional Black Start in the wake of the powerful hurricane that hit the south of the country. The storm damage left Kent and Sussex disconnected from the National Grid – but thanks to Black Start contingency plans, most people barely noticed. Kingsnorth Power Station restored power to the area and it ran independently, cut off from the rest of the Grid, until repairs enabled it to be connected up again."

Drax

A large amount of energy will be stored in EV batteries, but a proportion may be available to support restoration.

"By 2035 we'll have enough energy in the batteries in our vehicles to power the UK for two days"

Professor Malcolm McCulloch, University of Oxford at COP26 Twitter

Extreme weather events, due to climate change, may increase the probably of needing system Restoration. We need to be prepared.

RESTORATION

EV cold load pickup

If a power outage persists for hours, the load at restoration is typically higher than before the power cut. This is commonly due to loads such as thermostatic heaters restoring the water temperature to a target value. The effect is therefore known as "cold load pickup". This leads to high demand and an increased risk of overloading local infrastructure. EV charging will be a major addition to this effect.

Demand is forecast to increase by 50% over the next 20 years to support low carbon technologies. On top of that, cold load pickup is estimated to increase demand to over 200% of normal ADMD[1]. Due to the large and increasing capacity of EV batteries, this load pickup may be maintained for many hours, significantly longer than is currently seen.

This leads to a significant overload risk with the potential for physical damage to distribution substation equipment, as there is limited protection in the LV grid for overload from demand as opposed to protection for short-circuit faults. If instances of damage are widespread, this may disrupt the restoration process and may be perceived as being caused by NGESO even though the problems are limited to the distribution network.

Even without equipment damage, sustained high loads from re-energized EVs could slow down the rate at which restoration can be achieved.

1) Cold Start: Final Report

The UKPN Cold Start project (from 2020) forecast cold load pick up when 32% of cars on the road were expected to be EVs.

“Elevated demand has the potential to affect adversely the operation of the distribution network supplying the area of the outage: increased power flows may pull down voltages, cause network assets (both conductors and transformers) to overheat and in extreme cases may cause protection systems to operate, as well as causing unbalance between phase voltages due to the uneven split of LCTs between electrical phases.”

“The peak demand after outages can be more than double the no-outage value, both at the level of the whole network and in terms of per-customer demand.”

By the late 2030s Sygensys would anticipate an even higher cold load pickup unless robust mitigation systems are implemented.

Cold Start: Final Report

Wide scale adoption of LCTs will increase the scale of cold load pickup to the point where it could be unmanageable without new mitigation measures.

RESTORATION

ANM & the challenge of Restoration

The graphs show an ANM example from the WPD project "LV Connect and Manage". This case showed how ANM can manage EV charging demand to prevent the transformer limit being exceeded. Failure of this ANM-controlled smart charging system could lead to physical damage to the transformer.

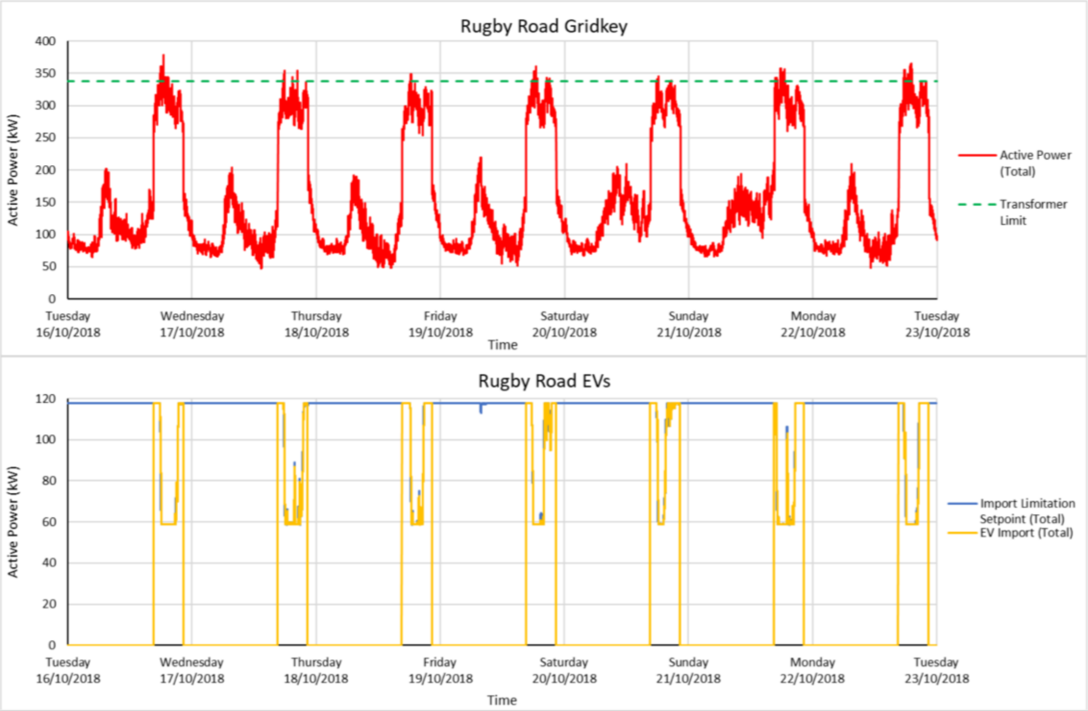
Consider an example of restoration after a 48-hour+ power outage. This would result in high power demand from both heating and EV charging, well over double the normal peak load. Centralised control may be impossible as ANM via DSR communication may not be available due to damage or lack of power for the smart charging communication infrastructure.

Customers are desperate for heat and mobility so as soon as power is restored, they use all the controls which are available to them to enable instant heating and charging. This may include smart charging override modes. The challenge to the DNO is to successfully re-energise whilst avoiding damage to the transformer or constraint-managed feeders.

DNOs recognise this challenge and some already limit the number of chargers per phase in some locations, partly due to cold load pickup concerns.

The large EV cold load pickup and the absence of EV DSR would also impact the load for ESO during restoration, making the restoration process more time consuming.

Live Trials: EV Charge Management (Import Limitation)



LV Connect & Manage Project Close-Down Dissemination Event 21st May 2019

Constraint management systems, including ANM, need to protect infrastructure during restoration, with large cold load pickup.

SYGENSYS

RESTORATION

Voltage control

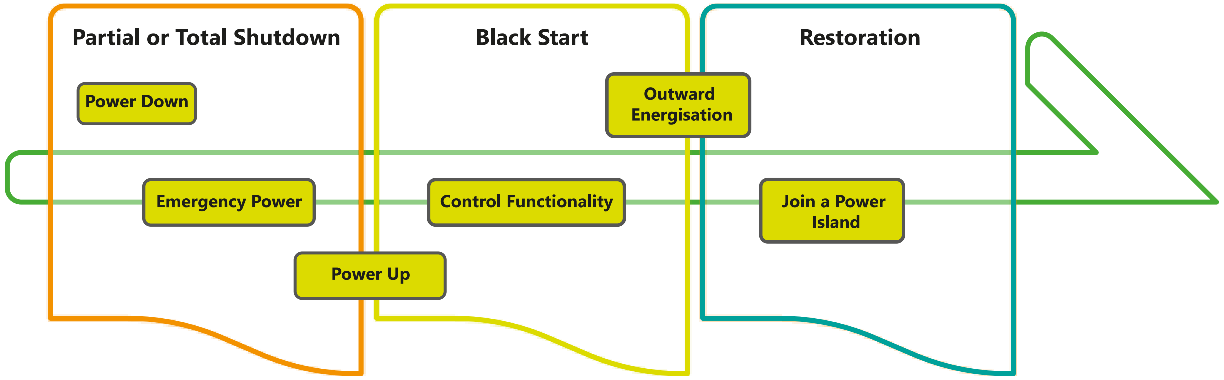
Voltage control is especially challenging during restoration. During this process, typically a generator will be started with no load, and then load is added in blocks. As each block is added, there is a load step and risk of under- or over-voltage conditions. Maintaining +/-10% voltage control[1] may be difficult, especially given factors such as the large transients during transformer energization.

EV chargers' voltage response makes this process more difficult because:

- EVs offer little or no load relief with voltage or frequency to help stabilise grid conditions.
- EV charging includes OVLO leading to load disconnection on over-voltage and the risk of cascade over-voltage tripping.
- The proposed G99-mandated low frequency response for V2G may cause all V2G-capable systems to export power to the grid during low frequency excursions, with the associated risk of over-voltage. Some block loads may unexpectedly become net exporting.
- Without communications for DSR control, EV chargers may default to charge at full power, increasing the cold load pickup.
- Alternatively, EVs may default to zero charging until internet communications and aggregator controls are re-established, leading to a delayed load step or ramp as communications are re-established.

1) Table 3.2 - Black Start from Non-Traditional Generation Technologies, National Grid ESO

Principal Stages of Black Start and Restoration



Category	Requirement		Definition
	Existing	Trial	
Time to Connect	≤ 2h	≤ 2h	Time taken to start-up the BS Plant from shutdown without the use of external power supplies, and to energise part of the Network, within two hours of receiving an instruction from the Electricity System Operator (ESO).
Service Availability	≥ 90%	≥ 90%	The ability to deliver the contracted BS Service over 90% of a year. Note: It is the responsibility of the Provider to demonstrate its service availability. By submitting a tender, the provider commits to ensuring availability at least 90% of each year of the service.
Voltage Control	Existent	Existent	Ability to control voltage level within acceptable limits during energisation/block loading (±10%).
Frequency Control	Existent	Existent	Ability to manage frequency level when block loading (47.5Hz–52Hz).

Black Start from Non-Traditional Generation Technologies, National Grid ESO

EVs with good fault ride-through and well-defined under and over characteristics for both voltage and frequency could actively support Black Start.

RESTORATION

EV support for island operation and restoration

The EV market is evolving rapidly. A reasonable analysis of existing chargers made as recently as 2019 (see right) will not be valid for EV charging systems going forward.

The marginal cost of adding V2G features is low as it largely impacts control software and does not require significant extra hardware. Consequently, in 10 years' time Sygensys anticipates that the majority of EV AC OBCM will support :-

- Vehicle to Grid (V2G), which will use Grid Forming controls and be able to provide reactive power and inertia services.
- Vehicle to Home (V2H) to provide back-up power to the home, where an isolation switch is used to disconnect the home from the grid.
- Vehicle to Load (V2L) to power ac devices directly from the vehicle, isolated from the grid.
- Communication for smart charging control

Given this feature set, V2G will be capable of playing a major role in day-to-day grid balancing and potentially during Restoration, together with the option to provide off-grid power during power cuts. Fully exploiting this capability will be a significant challenge, especially during Restoration where smart charging communication systems may be inoperative.

2019

"It is estimated that up to ten per cent of EVs would be available to provide V2G services in 2050"

Black Start from Non-Traditional Generation Technologies, National Grid ESO

2021

"VW intends that V2G will be included from 2022 on every electric car built on its second-generation MEB ("modular electrification kit") platform, will means not only VW electric cars but also sister brands Audi, Skoda and Seat-Cupra"

The Driven 2021/04/07

Elke Temme, the charging and energy boss of Volkswagen Group Components, said: "Bidirectional charging is a major boost to sustainability, because it turns cars into mobile power banks. Customers will be able to contribute to sustainability, but it will also be good for their wallet. If you do it right, you will effectively be able to charge your car for free at times."

Autocar 15 December 2021

Future plans for Restoration should look to fully exploit the capabilities predicted to be available from V2G in the 2030s.

DEMAND REDUCTION

Load Relief

In the event of insufficient Active Power generation being available to meet demand, the GB Grid Code makes provision for demand reduction in Operating Code 6 ("OC6")[1].

The first stage is based on voltage reduction. Grid Code OC6.5.3 assumes a 1.5% reduction in power for a 2% voltage reduction. This value has been confirmed in the mid 2010s by NIA projects including CLASS[2] and DIVIDE[3].

EV chargers are constant power within the normal operating voltage range, so lowering voltage by 2% will have little if any effect on their demand. Sygensys has measured similar effects in many other new converter-connected loads from motors with variable speed drives to LED lighting, confirming this trend within many LCTs.

As the amount of EV charging and other converter-connected load increases, the amount of voltage load relief is likely to reduce. Demand control by voltage reduction, and energy efficiency schemes based on conservation voltage reduction[4] will become less effective. To make up the shortfall in demand reduction for OC6, alternative services may need to be used, potentially at an additional cost in comparison to today.

Similar issues have been seen in other markets for frequency load relief; see opposite.

Changing frequency load relief in Australia

AEMO ensures there is enough frequency response in the system to deal with a single credible contingency, which is typically the loss of a large generating unit or major industrial load. The amount of contingency Frequency Control Ancillary Services procured is equal to the size of the largest credible contingency minus assumed load relief.

Historically, AEMO observed a 1.5% reduction in demand for a 1% reduction in frequency. With the changing nature of loads, they now only see a 0.5% reduction in demand for a 1% reduction in frequency. This increases the need for contingency services.

Load relief: AMEO

1) The Grid Code: OC6 Demand Control
2) CLASS Project
3) DIVIDE project
4) The value of conservation voltage reduction to electricity security of supply

Load relief will change rapidly over the next 10 years. We need to assess the impact it will have during contingencies and the need for ancillary services.

DEMAND REDUCTION

Reduced effectiveness of LFDD

The second stage of OC6 Demand Reduction[1] is Low Frequency Demand Disconnection (LFDD) operating at frequencies below 48.8 Hz in a series of steps.

V2G, like other embedded generation, reduces the effectiveness of LFDD, because when a DNO disconnects a feeder it will also inevitably disconnect embedded generation.

At some times of day, a feeder may even be net exporting. Currently there may be insufficient instrumentation to be sure of the impact before turning off a feeder. There have been examples in some countries of demand increasing during LFDD due to the high penetration of domestic PV. This issue is being actively addressed by NIA project SHEDD[2].

As the scale of V2G increases this becomes more of an issue, especially as V2G-capable systems may include a mandated power export at low frequency as proposed in G99.

These general issues also apply to OC6.7 Manual Disconnection

1) See clause CC.A.5.1 in the Grid Code
2) Project SHEDD

"LFDD tripping may have the effect of tripping Distributed Energy Resources (DER) situated within the demand block being disconnected by the LFDD scheme. This has the impact of removing both generation and demand at the same time thus potentially reducing the overall effectiveness of the LFDD action. Over time, predicting the overall level of demand that would be lost in a LFDD event consequentially becomes more complex to estimate as DER penetrations increase."

Appendices to the Technical Report on the events of 9 August 2019

Decreasing System Inertia

"In addition levels of system inertia are decreasing (e.g. due to the closure of large power stations) along with net transmission system demand. This reduces the effectiveness of LFDD schemes as changes in frequency will be faster and larger. Should the frequency fall at a high rate, more than one LFDD stage could operate resulting in too much demand being disconnected."

Low Frequency Demand Disconnection - WPD

"The effectiveness of the UFLS scheme is reduced by the reduced net load on UFLS circuits. This increases the amount of underlying customer load that must be shed to achieve the necessary arrest in frequency decline."

Trip of multiple generators and lines in Central Queensland and associated under-frequency load shedding on 25 May 2021

No one ever wants to get to the position where LFDD must operate, but it is a vital defence against wide-area system collapse.

MISCELLANEOUS

Non-compliant equipment

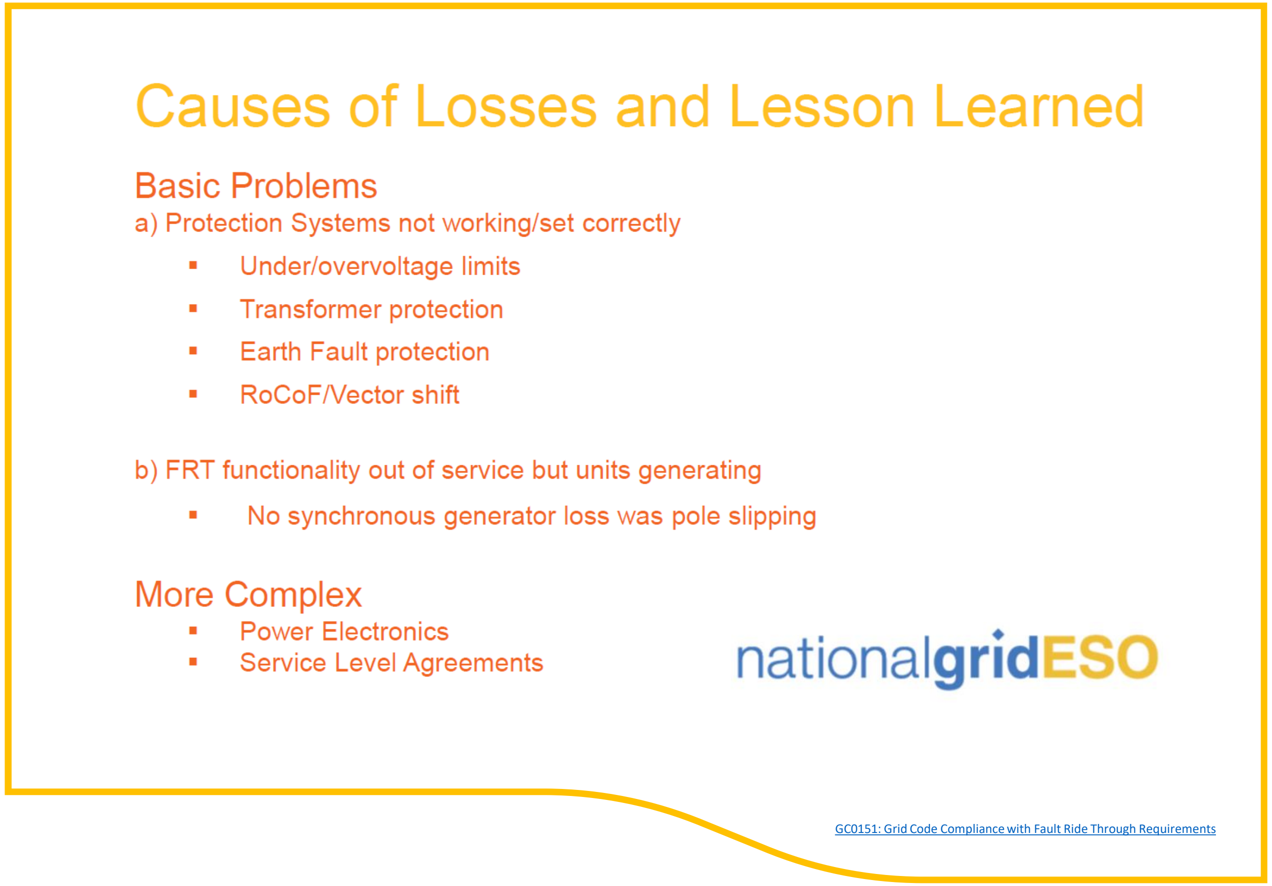
A key issue causing coincident tripping identified by ESO as part of working group GC0151 Grid Code Compliance Fault Ride-Through was non-compliant plant.

In general, plant may be non-compliant due to issues including

- Design
- Installation
- Maintenance
- Software update
- Deliberate or accidental mis-configuration
- Cyber attack

EV smart charging is likely to have similar issues to those listed above.

On top of this, if the impact on the consumer of smart charging controls is not palatable, there is a significant risk of them bypassing unpopular systems. This may include defeat devices or software jail-break to bypass mandatory smart charging characteristics. With tens of millions of EVs from a wide range of vendors, monitoring and enforcement of compliance will become very difficult.



Even when regulatory requirements are clear, unambiguous, timely and proportionate to the risks, some non-compliance is still likely.

MISCELLANEOUS

Rapid growth and unregistered capacity

To understand the potential response of the system when there is a grid transient event, it is essential to have a good understanding of the distribution of generation and demand across the grid. This is particularly challenging at times of rapid change, as anticipated over the next 10 to 20 years.

For behind-the-meter equipment, the ENA has defined a process[1] by which DNOs should be notified of the installation of LCT including PV, EV charging and V2G installations. Earlier versions of this process have not been particularly successful for PV, with a significant number of installations taking place without notification. This leads to a risk of overloads or un-forecast reverse power flows.

Lack of accurate data increases risks such as poor voltage control, enhanced voltage cascade risks and cold/black start overloads. For example, if installers were to fit several charge points on a heavily loaded feeder and not notify the DNO, there is a risk that when the multiple home-owners use them at the same time, this may overload the system leading to a local outage. The risks will be highest at daily peaks or during cold start, after a prolonged loss of supply.

1) ENA Connecting to the networks

"There is a notification process – an ENA form which should be sent to the relevant DNO – but this process is not consistently adhered to. The DNO is instead dependent on the incentive scheme to obtain insight of domestic installers. Most, though not all, consumers will currently use this; however if the scheme stops, this data source will dry up. "

Open Energy - Pilot - Confirmed EV Use Case

"A comparison of PV installations registered for the feed-in tariff (FiT) and with WPD's data shows only ~60% match in notified LV connections.

Despite forecasting, there is still a lot of uncertainty as connections might not materialise or might materialise in more abundance than expected. Rapid clustering of EVs can lead to overloads in the distribution network particularly if the electricity demand coincides with daily peak loading on the network. Similarly, rapid clustering of PV systems can lead to overloads but in the reverse power flow direction. Both situations put WPD's customers (both LCT customers and non-LCT customers) at risk of outages."

LV Connect and Manage Closedown report

During the forthcoming period of rapid increase in demand it is critical to forecast and monitor the local loads to assess the need for ANM and reinforcement.

MISCELLANEOUS

Low short circuit level with high levels of V2G

V2G, like all inverter-based resources, normally does not provide high fault current. Typically, it will provide only just over 100% of the current required for full power. This is very low compared to synchronous generators which may provide 500%.

At times of high contribution from V2G to total generation capacity, this could lead to a further lowering of Short Circuit Level[1] (SCL). This presents many challenges for protection systems, voltage control and stability of other IBRs.

Of particular concern in Project REV is the performance of PLLs in the power converters of EV chargers and V2G. Low SCL can lead to widespread low voltages during a fault and potential loss of synchronization between PLLs and the grid phase, creating an enhanced risk of coincident tripping. These transient voltage events are often combined with a rapid change of frequency, increasing the challenge to PLL operation.

Advanced V2G systems with Grid-Forming controls, which may be common in the 2030s, are likely to contribute "synthetic" inertia to help stabilise grid frequency. However, they are still unlikely to offer fault current injection that would increase SCL, as this would directly impact the unit cost.

SCL	Effect on the system
High SCL In a high SCL system during a fault voltage will fall, but it will quickly recover once the fault is fixed. The voltage will settle down to normal condition quickly with only small oscillations.	
Low SCL In a low SCL system the voltage will still fall during a fault, however it will experience oscillations as it starts to recover. The voltage will settle down to normal conditions but this will happen slowly and voltage will fluctuate during this period.	
Very Low SCL In a very low SCL system, the voltage behaves in a similar manner to the low SCL system, however instead of recovering to normal conditions the oscillation will continue or increase.	

Declining SCL can impact operability in several ways:

Protection	Voltage	Stability	Converters
Lower SCL means protection sees smaller (or different) currents than it was expecting & may not work	Lower SCL means that voltage moves faster and to a greater extent when there is a disturbance on the system	The lower system strength means that the system may not be able to return to normal operation after a disturbance	The faster moving voltage caused by low SCL can mean that converters may not know what the system is doing and how to respond

SCL impact on Phase Locked Loop (PLL) converters

- Short circuit level is required to maintain a stable voltage during a fault period which then informs the PLL
- The decline in short circuit level means that the PLL converters may not keep reference with the system during a fault period
- This poses a risk that multiple generators will be affected by a fault adversely

System Operability framework Impact of declining short circuit levels

1) What is short circuit level?

Low SCL will impact PLL operation in EV chargers and V2G with a risk of coincident tripping. V2G will also contribute to falling SCL.

MISCELLANEOUS

Smart charging cyber security

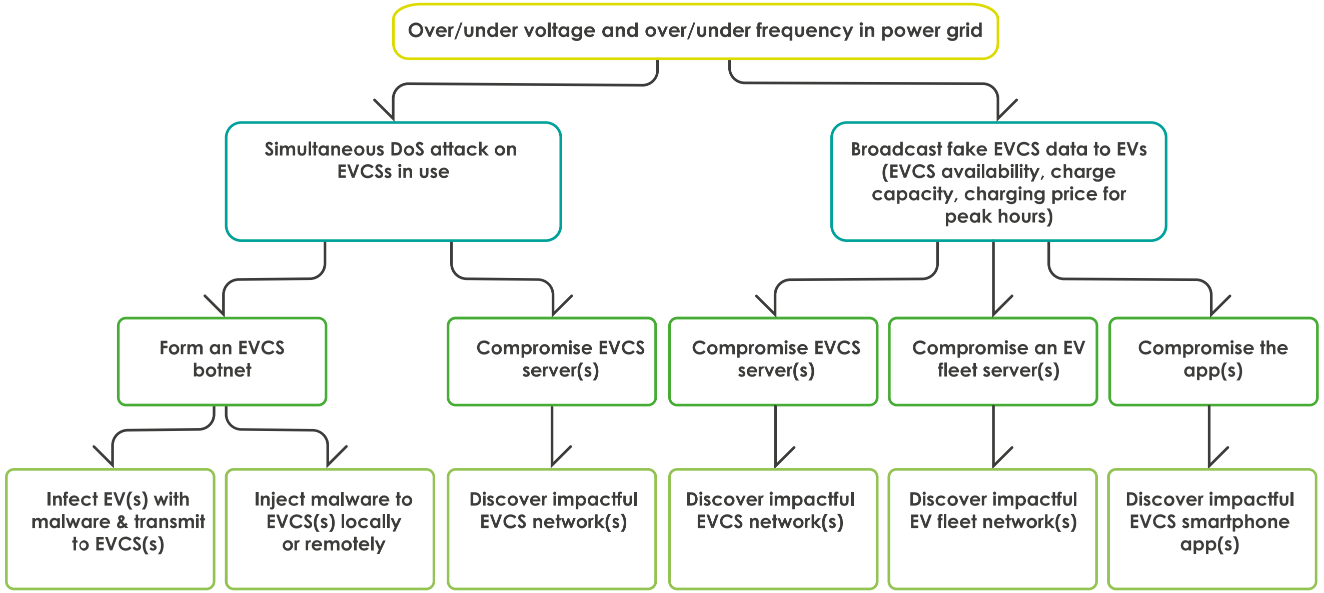
Cyber security for smart charging has been considered extensively, for example in "Securing the Electric Vehicle Charging Infrastructure[1]". Smart charging operation can be complex and may involve many different interconnected systems.

As with many interconnected devices, existing EV charger technologies have been shown to have security vulnerabilities. There is a need for improved specification, design, implementation and maintenance. However good these systems become, however, there are likely to be ongoing cyber challenges which may range from tariff evasion to ransomware.

As smart charging becomes a key mechanism in grid balancing, it is important to consider the potential impact of a cyber attack on grid operability. For example, some cyber attacks could adversely impact ANM constraint management, even if that were not the principal target of the attack.

Analysis of the impact of Distributed Denial of Service (DDoS) cyber attacks may help inform planning for restoration where communications systems may be highly degraded.

1) Securing the Electric Vehicle Charging Infrastructure State-of-the-art review and recommendations with a focus on smart charging and vehicle-to-grid

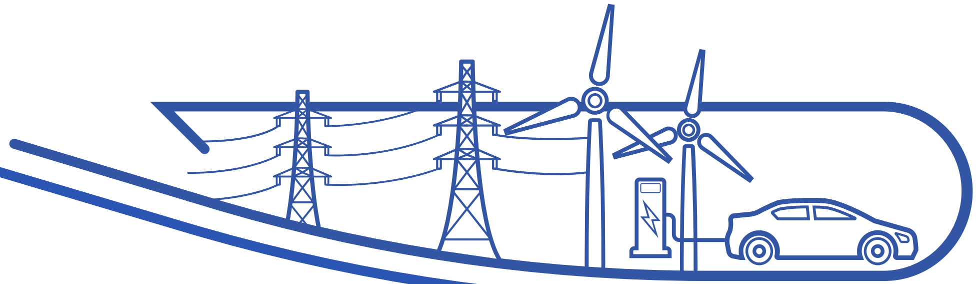


Cybersecurity of Smart Electric Vehicle Charging: A Power Grid Perspective

"U.K. cybersecurity company Pen Test Partners has identified several vulnerabilities in six home electric vehicle charging brands and a large public EV charging network. While the charger manufacturers resolved most of the issues, the findings are the latest example of the poorly regulated world of Internet of Things devices, which are poised to become all but ubiquitous in our homes and vehicles."

Techcrunch August 3, 2021

Maloperation of DSR from EVC and V2G could destabilize the grid so these systems need a high level of cyber security.



CHAPTER 7
Summary

Challenges for the System Operator from large scale EV charging/V2G

This Project REV WP1 report highlights the risks to grid short-term stability and fault recovery in order to raise awareness within the industry. It does not, at this stage, aim to present potential mitigation solutions.

Brainstorming was used to identify a broad range of issues which may have a negative impact on the grid. Some of these issues may be minor, some are already being addressed. Many will need further mitigating actions over the next few years ahead of mass adoption of EVs.

The findings we have presented as challenges for grid operators include DNOs but are principally focussed on ESO. We identified some potential direct impacts on consumers and challenges for charging system suppliers who are likely to be key to implementation of some of the required mitigation.

The initial assessment of the need for mitigating actions is summarized in the table to the right on a Red, Amber, Green (RAG) scale.

Summary of the top challenges for electricity system operation identified in WP1

Status	Risk	Explanation
R	Load step (Increase or decrease)	Time-driven; Time of Use tariff step, clock change Event-driven, eg software update/bug, cyber attack
R	Load ramp (Increase or decrease)	Randomised EV switch-on or off creating a large ramp Automatic "Panic buying" response to NGESO margin notice or weather forecast
R	Coincident tripping	PLL unlock, cascade tripping (high or low voltage), RoCoF tripping, charger de-load, V2G delayed return after fault
A	Stability	Unintended controller interactions, unclear control primacy, 10GW V2G with low SCL, no inertia or PSS, Onerous load response characteristic, cyber attack
A **(R for DNOs)**	Restoration (Black Start)	Smart charging DSR dependency on communication, risk of tripping on high/low voltage, high cold load pickup, unpredictable load return timing,
A	Other	Reduced effectiveness of voltage reduction and LFDD. Realtime observability and post-event forensics difficult with EVC and V2G

Colour	Risk	Mitigation
Red	High	Essential
Amber	Medium	Desirable
Green	Low	Optional

The challenges identified need to be investigated and appropriate mitigation implemented where required to maintain cost effective security of supply.

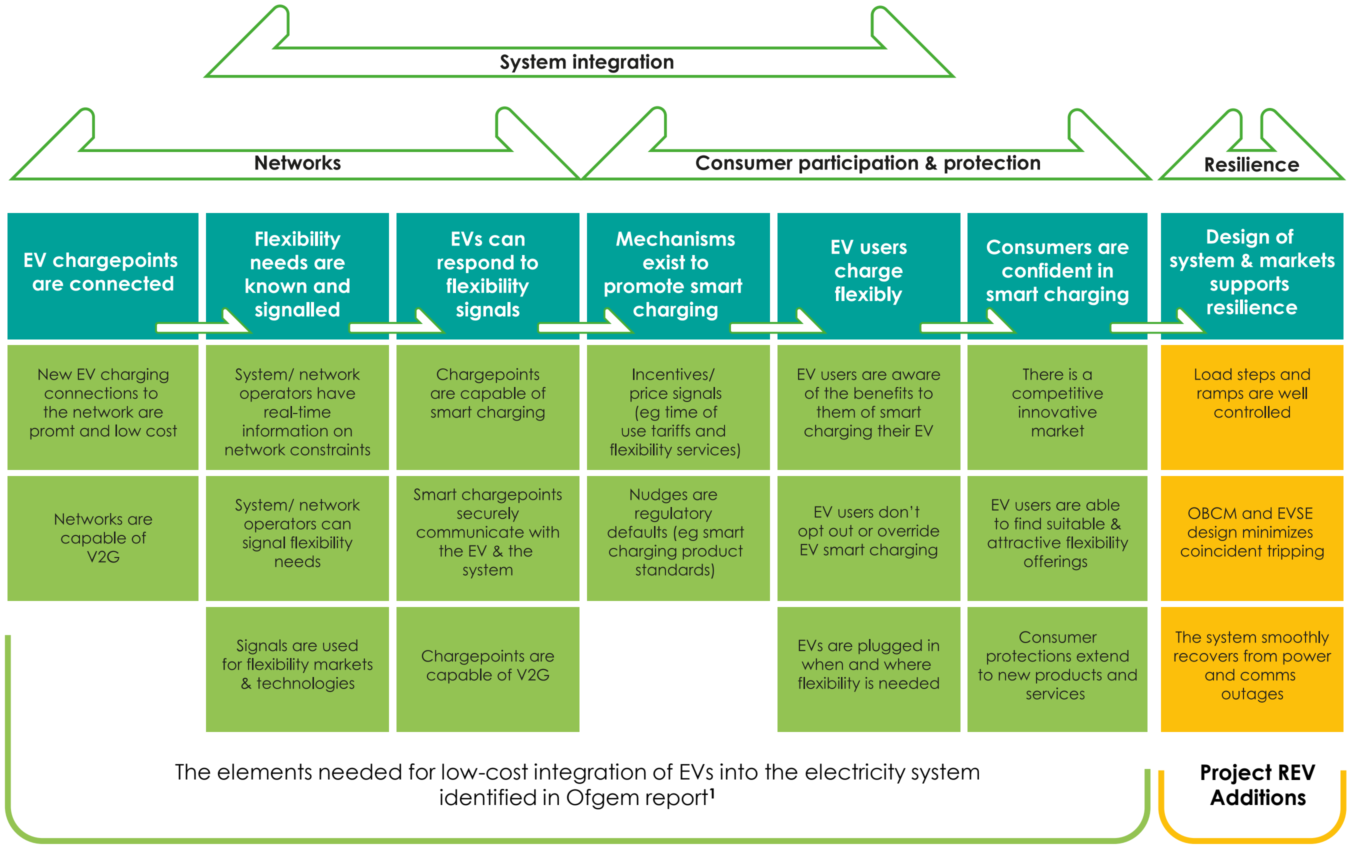
EVC and V2G have significant implications for grid resilience

The vast majority of studies looking at the impact of EVs on the grid to date have focused on power, energy and peak load requirements, along with smart charging control. This Project REV report has highlighted the fact that the dynamic behaviour of EVs under both normal and abnormal operating conditions could present a significant risk to system resilience.

To cost-effectively maintain and enhance grid resilience, it is important to consider the impact of the complete smart charging system on both balancing costs and resilience during

- Normal operation
- Grid transient events
- Restoration
- Communication and control system faults
- Cyber attack

We anticipate that these issues can be successfully addressed over the next few years, but there are potential impacts across the electricity and EV supply chains. There is also scope for shared learning and interoperable control systems for other domestic smart energy appliances such as BESS, HP, roof top PV and storage heaters.



1). Enabling the transition to electric vehicles: The regulator's priorities for a green, fair future

The impact of mass smart EVC and V2G have significant implications for grid resilience.

Next Steps

During WP1, Project REV aimed to answer the question "How could EV charging make the grid less stable?" and went on to identify numerous mechanisms in this report.

We have highlighted the potential causes of, and need to effectively manage, the risks associated with load steps and ramps. This should be addressed by regulation, market design and standardisation activities alongside EV-based DSR system implementation.

In WP2 we will undertake simulation studies to identify the scale of impact that EV adoption could have in other areas of grid stability. This will focus on issues related to coincident tripping and the changing voltage sensitivity of loads. We plan to study topics such as

- RoCoF triggering of V2G inverters
- Tripping of EVC and V2G due to voltage effects including during Restoration
- Impact of EV load relief characteristics on network stability

We anticipate that most of the issues identified can be addressed by enhanced design of EVC and V2G products, control systems and markets. This could lead to enhanced grid stability and security of supply. In WP2 we will estimate the potential financial benefit of EV DSR by 2030.

"Electric vehicles will revolutionise the way we use energy and provide consumers with new opportunities, through smart products, to engage in the energy market to keep their costs as low as possible.

Our electric vehicle priorities not only provide a way to meet our climate change targets but importantly offers ways to protect consumers from rising bills, through a three-prong approach of increased use of electric vehicles, smart charging and vehicle-to-grid technology which together can help drive down costs for all GB bill payers."

Neil Kenward, Ofgem's Director of Strategy and Decarbonisation

We would welcome feedback on the preliminary findings in this report, from NGESO as well as from participants in the EV charging supply chain including vehicle and charge point designers and manufacturers, operators, aggregators, DNOs, regulators and consumer groups.

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