H2020-LCE-2016-2017

EUROPEAN COMMISSION

European Climate, Infrastructure and Environment Executive Agency (CINEA)

Grant agreement no. 731249

SMILE

Smart Island Energy Systems

Deliverable D2.7
Report on 24 months of system operation

Document Details

Due date	31-10-2021
Lead Contractor	OVO Energy
Version	Final rev0
Prepared by	OVO Energy/OVO Field Force
Input from	OVO Energy/OVO Field Force, Community Energy Scotland (CES), Sunamp, Route Monkey, Lithium Balance
Reviewed by	RINA Consulting S.p.A.
Dissemination Level	Public

Project Contractual Details

Project Title	Smart Island Energy Systems
Project Acronym	SMILE
Grant Agreement No.	731249
Project Start Date	01-05-2017
Project End Date	31-10-2021
Duration	54 months

The project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No 731249

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1 Introduction

The overall scope of SMILE project is to demonstrate, in real-life operational conditions, a set of both technological and non-technological solutions adapted to local circumstances targeting distribution grids to enable demand response schemes, smart grid functionalities, storage, and energy system integration with the final objective of paving the way for the introduction of the tested innovative solutions in the market in the near future. To this end, three large-scale demonstrators have been implemented in three island locations in different regions of Europe with similar topographic characteristics but different policies, regulations, and energy markets: Orkneys (UK), Samsø (DK) and Madeira (PT).

The aim of this report is to provide an assessment of the operation of the Demand Side Management (DSM) system on Orkney demonstrator after 24 months, during which the DSM system has been further optimised.

It starts with a background to the unique grid situation in the Orkney archipelago and introduces the problem of wind turbine curtailment, and describes at a high level how the DSM system developed during the SMILE project can help to mitigate wind turbine curtailment. It then describes, for each installation type, how the system was both physically and algorithmically configured to deliver curtailment mitigation, and discusses the system's effectiveness in mitigating curtailment as well as the learnings from the project for each type. It ends with a section on curtailment response effectiveness across all systems followed by a section that describes overall learnings from the project, both of which can be invaluable to others trying to innovate in the space of mitigating grid constraints using residential demand flexibility.

2 Orkney Background

The Orkney Islands, an archipelago situated off the north coast of mainland Scotland, generate on average over 120% of their electricity needs through the islands' 52MW of renewable energy; the majority of which is wind (large and micro scale) and solar. Any excess generated electricity is transported to the Scottish mainland via two subsea distribution cables. In reality, generation from Orkney's wind turbines is far higher. When the capacity limits within areas of Orkney's grid network are reached, wind turbines in that area begin to be switched off - known as being curtailed. Turbine curtailment not only reduces renewable generation, it also threatens the financial viability of wind generation on the islands. This is a concern, as many turbines in Orkney are community-owned, with revenue from the turbine going directly back into the community.

Rousay, Egilsay & Wyre is a three-island group within the Orkney Islands, with a population of c. 260. With the Western Isles, Orkney generally has one of the two worst local authority fuel poverty rates in Scotland, with the Scottish Government reporting figures showing that close to 60% of households are classed as being in fuel poverty consistently over the past decade. Fuel poverty is defined as a household where fuel costs are more than 10% of their net income.

Despite this, large-scale wind turbines have been present in Orkney since 1985 and since the early 2000's, when the first modern large-scale wind turbines were installed in the islands, there has been a steady increase in local renewable energy generation. It is estimated that large scale wind generates approx. 161 GWh per year, while small scale wind generates approx. 19 GWh per year. Export to mainland Scotland occurs via two 33kV submarine cables. Since 2012 however, Scottish Hydro Energy Power Distribution (SHEPD) imposed a moratorium on all new generation, of more than 16A per phase, in the islands due to grid constraints.

Since 2009, an Active Network Management (ANM) system has been in operation across Orkney, to allow generators to connect and export to the limited grid system without the need for substantial upgrades to the network capacity. This however has introduced the risk that their generation may be limited due to the grid constraints. The ANM monitors power flow through pinch points on the grid network and power flow from a number of renewable energy generators to be controlled in order to reduce their output to match available network capacity. This results in what is known as the 'curtailment' of generators.

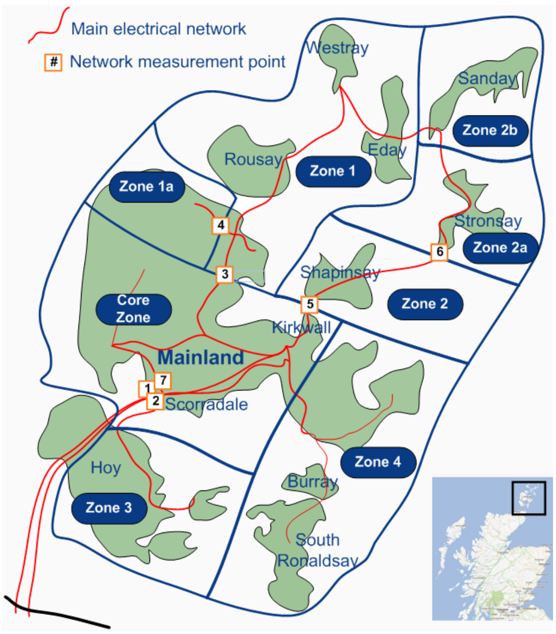


Figure 1: The Orkney ANM, showing the various zones of the local network

Before the introduction of the ANM and latterly, the moratorium, several local development trusts and community groups were able to receive grant funding and raise capital to install their own renewable energy generators. The Rousay, Egilsay and Wyre Development Trust (REWDT) oversaw the commissioning of their 900 kW Rousay wind turbine in 2011, two years after the introduction of the ANM system, which means that the turbine is managed on a **non-firm grid connection**.

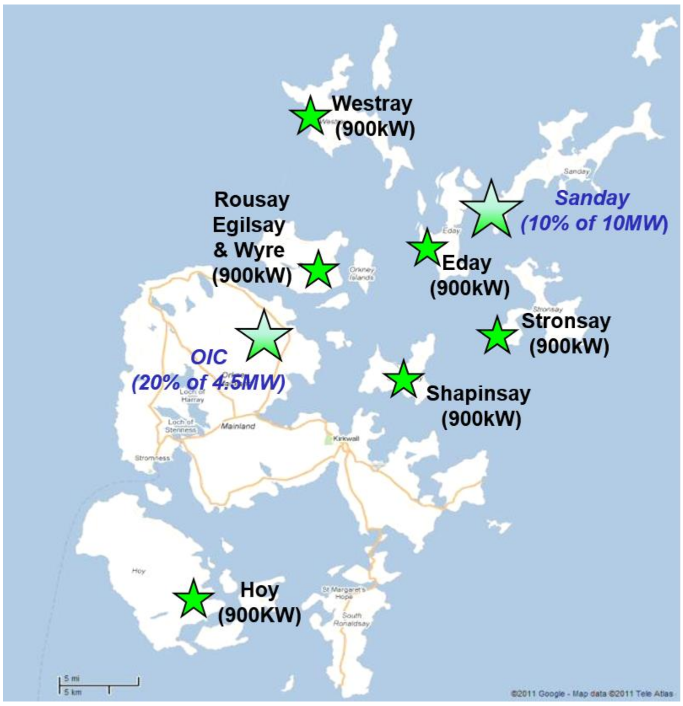


Figure 2: The Rousay, Egilsay and Wyre community turbine, alongside other large scale community owned renewable energy generation. Total installed: c. 7.3MW

The Principles of Access (PoA) mechanism used in the ANM prescribed a Last-In First-Out (LIFO) system, which meant that many of these community owned turbines were connected as **new non-firm generation**. As new non-firm generation, the turbines would be subject to control from the ANM which meant that their exports could be 'curtailed'. These generators were in contrast to those connected to the Distribution Network Operator (DNO) earlier and marked as **firm generation**, where they would receive priority to access the grid. This is known as the **priority stack**, where generators further down in the stack (and therefore the last to be connected to the DNO) are given lower priority to access the grid, meaning many of the later generators were subject to more frequent curtailment, ultimately resulting in reduced generation.

As a result of the priority stack and the LIFO principle, at times of peak potential generation resulting from optimal generation conditions, overall export to the grid tends to be very high. Therefore generators further down the priority stack are likely to be curtailed. This causes a significant problem for lost income from generation for many turbines across various zones. It is estimated that the curtailment of the community turbines has resulted in double digit percentages loss of production amounting to losses well over £100,000 per annum for the island economies. The results of such significant curtailment proves to be a problem for the development trusts and their turbine trading subsidiaries. In the worst case scenario, the trusts can struggle to meet their loan repayments remaining from the financing and installation of their turbines. However a reduction in income through reduced export to the grid also reduced capacity to tackle issues in their communities, such as island depopulation, high fuel poverty, old existing housing stock and a lack of employment opportunities.

3 SMILE DSM System

The SMILE project sought to build on the legacy of previous projects in the Orkney islands (e.g. Heat Smart Orkney that demonstrated how electric loads can be used to mitigate the aforementioned issues), by installing and intelligently controlling seven different configurations of flexible electric loads - various configurations of electric heat systems and electric vehicle chargers - to reduce the curtailment of community wind turbine generators on Orkney. This was facilitated by OVO via its energy flexibility platform Kaluza as follows:

- A Kaluza platform connected "VSCon" unit installed at the Rousay and Eday turbines relayed to the platform instructions sent to the respective turbine about their curtailment status; and
- Algorithms running on the Kaluza platform turned on available flexible loads during periods of marginal curtailment of the Rousay and Eday turbines, while not affecting the customer's primary need (such as managing their home heating needs, or having a sufficiently charged electric vehicle when they need it) from these appliances.

The overall SMILE DSM system architecture implemented in the Orkney is illustrated in Figure 3.

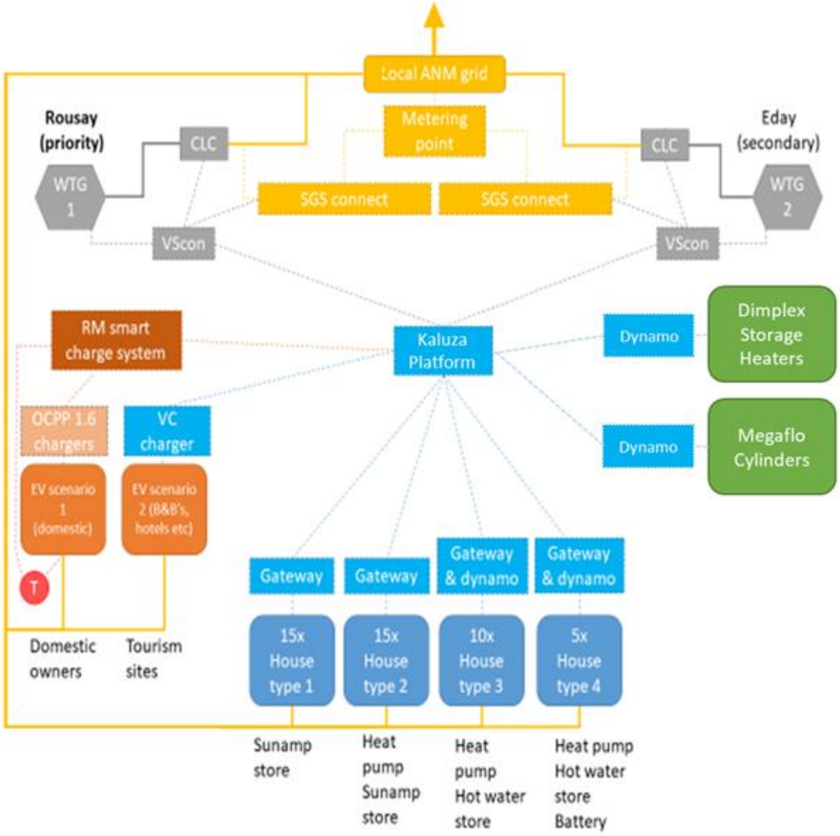


Figure 3: Overall DSM system architecture

In particular, 4 different types of installations were implemented at residential level

- Type 1: based on the Sunamp PCM Heat Battery
- Type 2: based on the Sunamp PCM Heat Battery combined with Heat Pump
- Type 3: based on Heat Pump combined with Hot water store
- Type 4: based on Heat Pump, hot water store combined with Battery Energy Storage System (BESS)

Furthermore, 2 different solutions were conceived for electric vehicle smart charging:

- Type EV Indra: based on an Indra Smart Charger installed at tourism sites like B&Bs and hotels
- Type EV Trakm8: based on a OCPP1.6 compliant charge point installed at domestic owner sites

Finally, aggregated controllable heat load consisting of storage heat and hot water cylinders - installed originally as part of previous projects on the islands - were added to the DSM system and is referred to as “Type Aggregated Heat Load - HSO”.

The remainder of this document details how these various system types were set up to manage both the customer needs as well as to mitigate curtailment, and our overall learnings from the SMILE project.

3.1 Wind Turbine Installation Configuration

In addition to the installation of the various types of systems outlined in the previous section and detailed in the upcoming sections, equipment was also installed at multiple wind turbines in order to receive telemetry from both the wind turbine, and the active network management (ANM) system. The data from both of these devices was necessary to detect both when the turbine is being curtailed, and the power output of the wind turbine.

The schematic in Figure 4 shows the configuration of the equipment installed in the wind turbine control room.

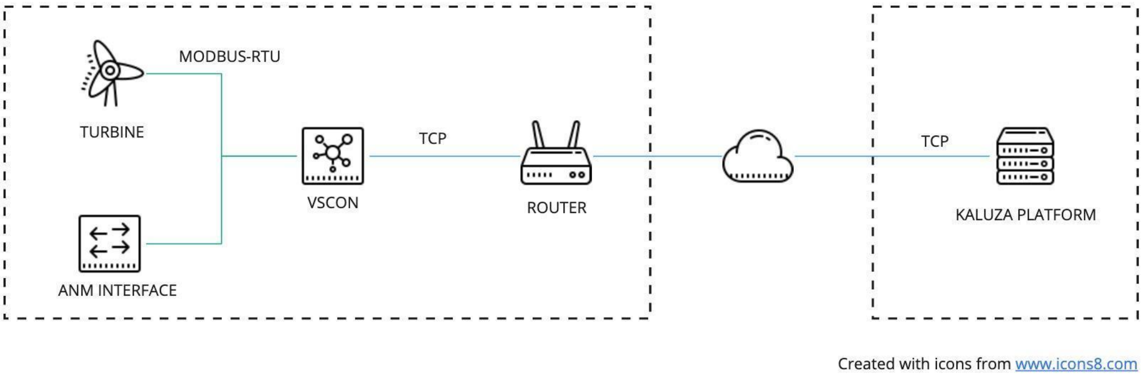


Figure 4: Schematic of the equipment installed in the turbine housings in Eday and Rousay

The VSCON (VCharge SCADA Connect) device enables the SCADA equipment located in the wind turbine housings to be connected to the Kaluza platform. The VSCON interfaces with the turbine controller and the ANM interface over MODBUS-RTU or MODBUS-TCP and transmits the register state data to the Kaluza platform. This enables the Kaluza platform to receive real-time turbine telemetry, including the power set point as well as the actual power output. This enables the platform to determine when the wind turbine is curtailed, as illustrated in Figure 5.

Figure 5: Graph Illustrating the setpoint and active power of the Eday turbine. In this example, highlighting two periods during which the turbine was curtailed

For the purposes of the Orkney SMILE project, curtailment events as they occurred at the Rousay and Eday turbines in Orkney were considered. For a significant period in 2021, the Eday turbine was unavailable, due to Eday's two subsea power cables failing forcing the island to run off a diesel generator set, and therefore most of the project's curtailment mitigation impact was driven by curtailment events at the Rousay turbine.

"Curtailment events" occur when a particular turbine is "marginally curtailed". A turbine is defined as "marginally curtailed" when the setpoint it receives from the ANM system associated with the turbine is:

- Greater than 0 kW - a state known as "fully curtailed"
- Lesser than 900 kW or the maximum power that the turbine can produce - a state known as "uncurtailed"

The reasoning for not considering a setpoint of 0 kW as an "curtailment event" for a particular turbine is because: when the setpoint is at 0 kW, the turbine is fully curtailed and the curtailment signal has moved on to the next turbine in the curtailment stack; and any curtailment mitigation that happens from the SMILE asset portfolio, given their overall capacity to deliver curtailment mitigation, is unlikely to change the setpoint of the particular turbine in question so that it can go from fully curtailed to marginally curtailed.

Additionally, for the purposes of the curtailment effectiveness analysis in this report - we have only considered marginal curtailment events that lasted at least 60 seconds. This allowed us to focus on marginal curtailment events where the end to end system had sufficient time to initiate a curtailment response across various system types.

3.2 Type 1

3.2.1 System Configuration

The Type 1 system installs are principally based on Sunamp UniQ thermal PCM (Phase Change Material) batteries with the capability to be heated by either the property's existing heat source or the battery's internal electrically powered heating elements. Figure 6 and Figure 7 detail the system schematics for both electric and wet system sub types, with equipment installed for the SMILE project highlighted in white.

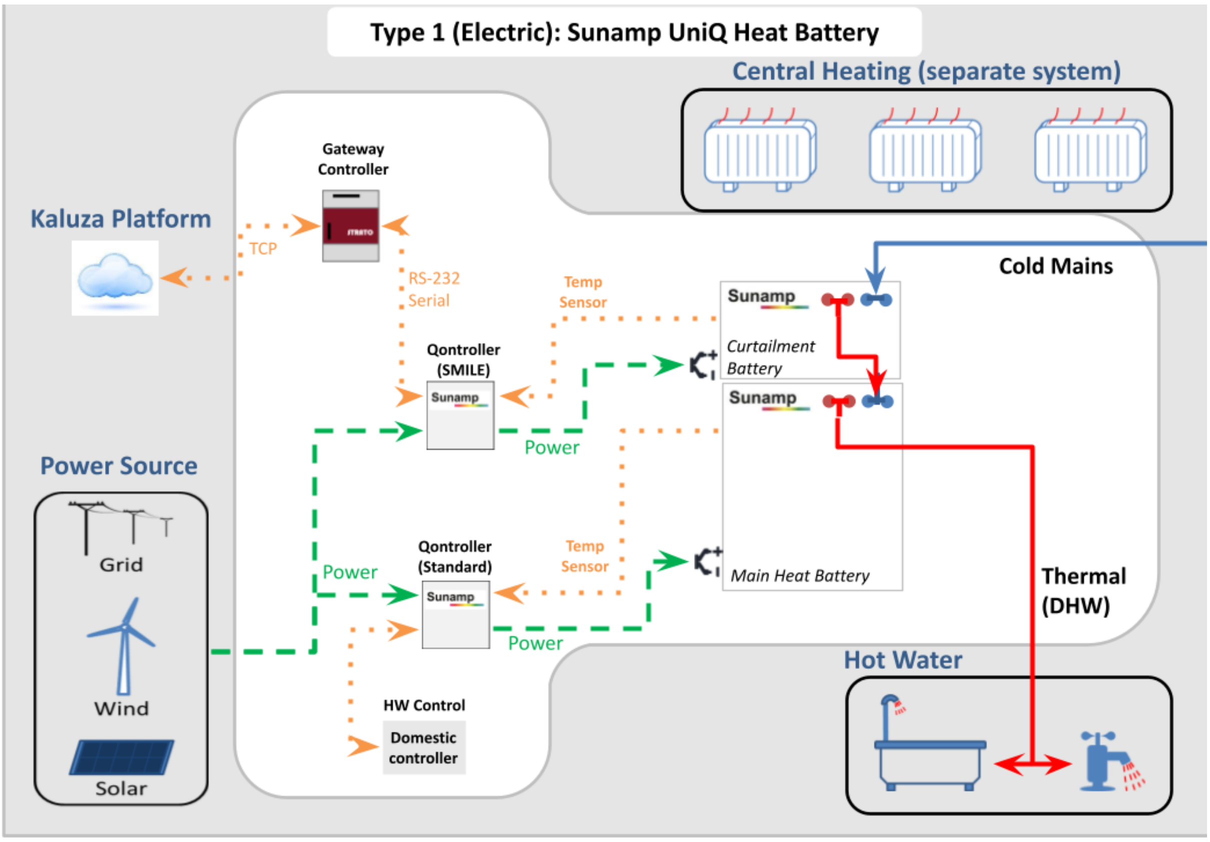


Figure 6: Type 1 system (Electric) hydraulic configuration

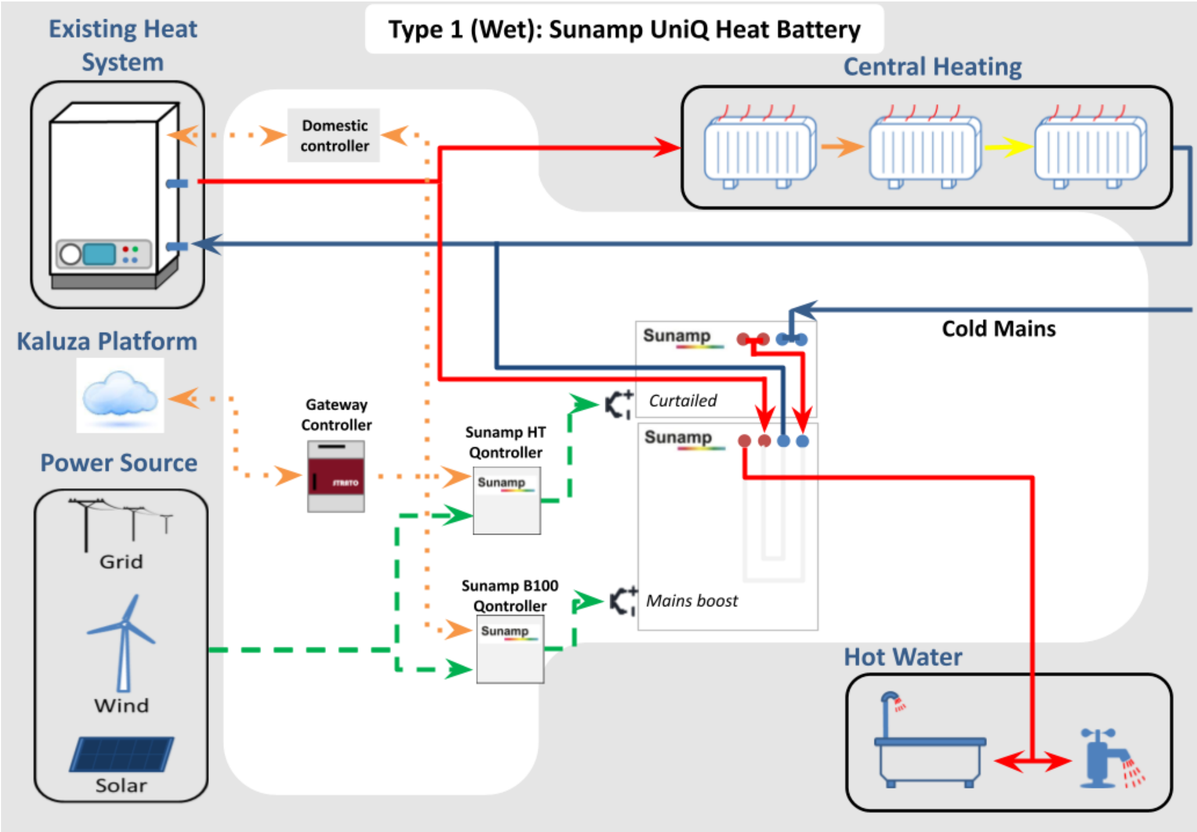


Figure 7: Type 1 system (Wet) hydraulic configuration

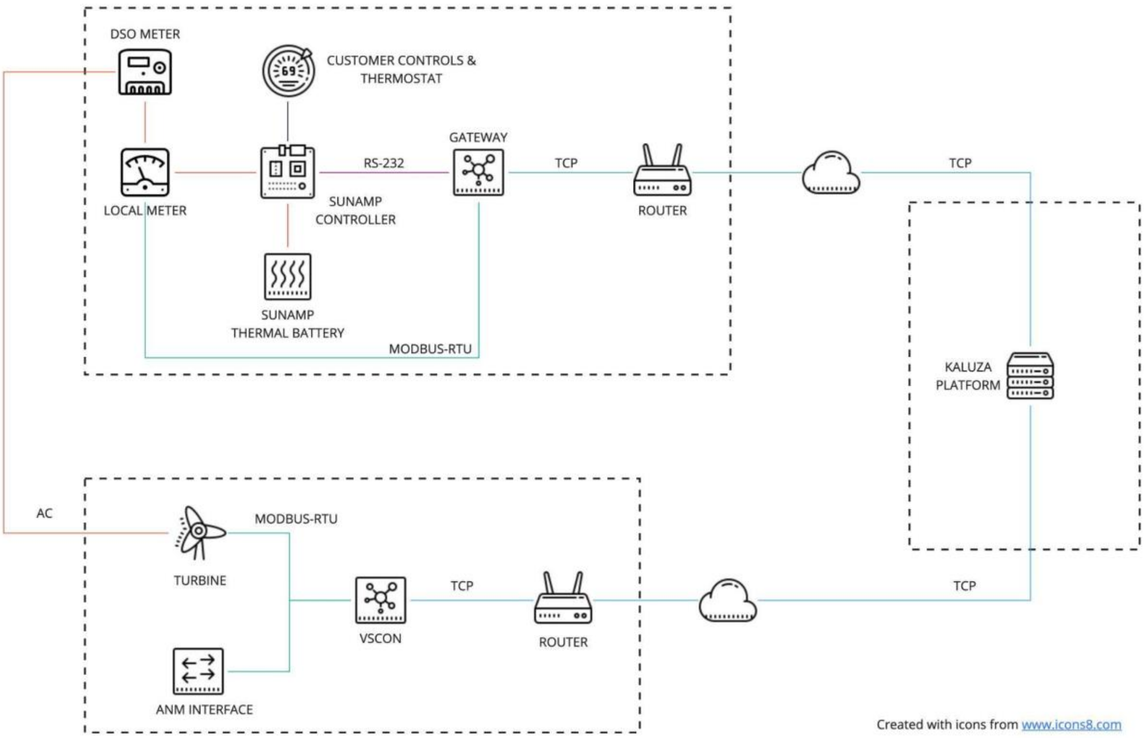


Figure 8: Type 1 system control and integration configuration

The power demand of the Sunamp PCM heat batteries available for installation with internal heating elements are rated at 2.8kW @ 230V, or multiples of this if installed in conjunction with additional units in order to meet greater thermal demand. The storage capacity of the installed units can be scaled by installing additional UniQ units in order series and/or parallel to meet the specific required demand of participating households; principally dependent upon the daily requirements of hot water.

Given that the UniQ units are available both with and without the internal electrical heating element, at least one unit with the internal element was installed in each property that could be charged with curtailed energy to ensure a rapid response to a curtailment event.

Figure 8 illustrates the end to end control integration between the Type 1 on-site installation, the wind turbines and the Kaluza platform. The functionality and connectivity of each component is described in Table 1.

Table 1: Components and functionality of the Type 1 system

Component	Description/Specification	Connectivity	Location
VSCON	The VSCON unit monitors for, and transmits curtailment information from the wind turbine and the local smart grid (ANM interface).	Modbus-RTU/TCP from the wind turbine and ANM interface. Ethernet (TCP) to onsite router.	Wind Turbine
Kaluza Platform	Cloud-base control aggregator responsible for the smart functionality controlling of all equipment (either directly or indirectly), on both the generation and demand side of the SMILE infrastructure.	TCP connection over the public internet between internet routers located at wind farms and customer homes.	Kaluza Data Centre
Kaluza Gateway	The Kaluza Gateway provides on-site control of equipment by relaying information from the Kaluza platform, and also returning data back again for processing.	Ethernet (TCP) from onsite router, and RS-232 serial link to the Sunamp controller.	Customer's Home
Sunamp Controller	Controller unit dedicated to the control and monitoring of Sunamp PCM heat battery. In this configuration, the controller acts as the conduit between Kaluza	Controlled by the Kaluza Gateway unit via RS-232 serial bus.	Customer's Home

	platform control signals and the charge/discharge control of the PCM heat batteries.		
Sunamp PCM Heat Battery	Stores thermal energy. Scaled to required size in units of 2.8kW power, with storage capacities of 3, 6, 9 and 12kWh. Thermal energy stored in Phase Change Material solutions in sealed products. An internal heat exchanger transfers heat either to or from water flowing through the battery depending on charging or discharging.	Controlled by Sunamp Controller via RS-232.	Customer's Home
Local meter	A 100A power meter installed in the consumer unit to measure the power consumption of the SMILE-specific heating components	MODBUS-RTU to the Kaluza gateway	Customer's Home

The specific Type 1 configurations installed during the project are listed in Table 2

Table 2: Quantity and type of Type 1 systems installed

Type 1 Configuration	Number of properties installed
Type 1 (Electric)	10
Type 1 (Wet)	4

3.2.2 Curtailment Operation

At a high level the curtailment mitigation system using Type 1 can be described as follows:

- Energy delivered through the property's existing heat source is stored separately ("primary storage") from the energy delivered through the battery's internal electrically powered heating elements ("supplementary storage")
- The curtailment mitigation system does not interact with the primary storage and only interacts with the supplementary storage. Primary storage is managed purely based on a timer

schedule as determined by the resident and the installer, and supplementary storage is purely managed by Kaluza platform's curtailment mitigation system

- When a turbine is marginally curtailed ("curtailment event"), Kaluza platform instructs the battery's internal electrically powered heating elements to turn on ("override on" mode) so as to deliver energy to the supplementary storage - so long as the curtailment event occurs during the off-peak window of the resident's energy tariff.

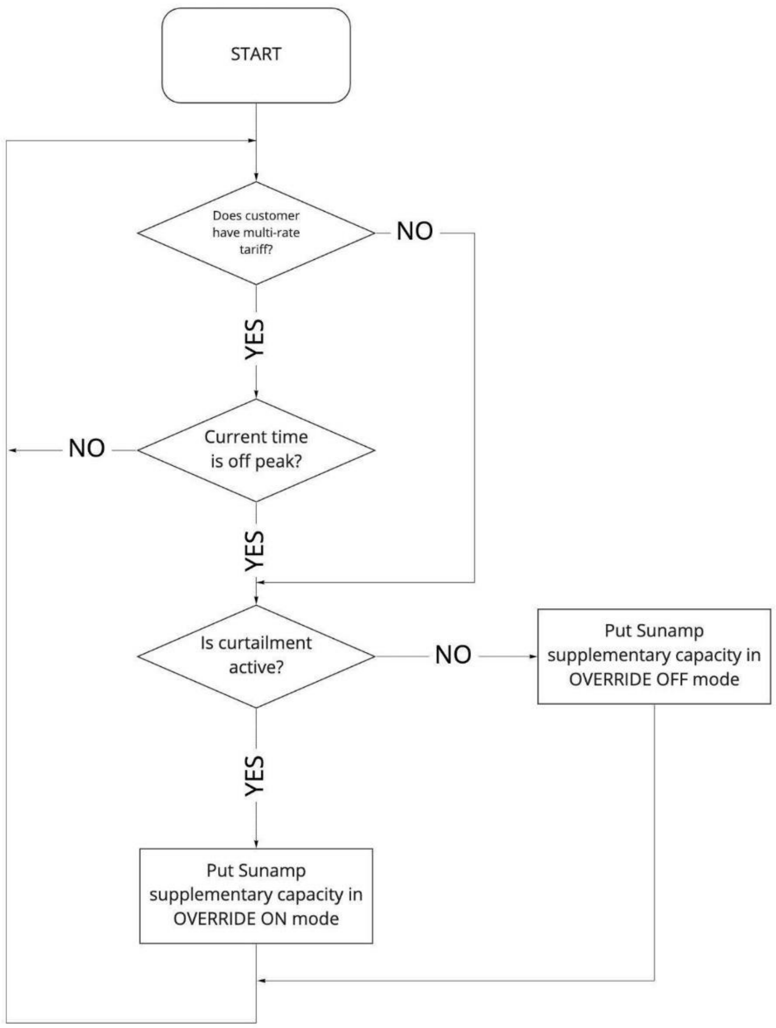


Figure 9: Type 1 control algorithm

Figure 10 below illustrates a curtailment event at the Rousay and Eday turbine and a Type 1 system's response to it. The first chart shows the setpoint of the Rousay turbine. The second chart shows the setpoint of the Eday turbine. The final chart shows the response of the Sunamp unit. As seen in the chart, from around 13:20-13:20 both the turbines are fully curtailed with a setpoint of 0 kW. During this time, the Sunamp unit is in "Override off" mode, as seen in the final chart.

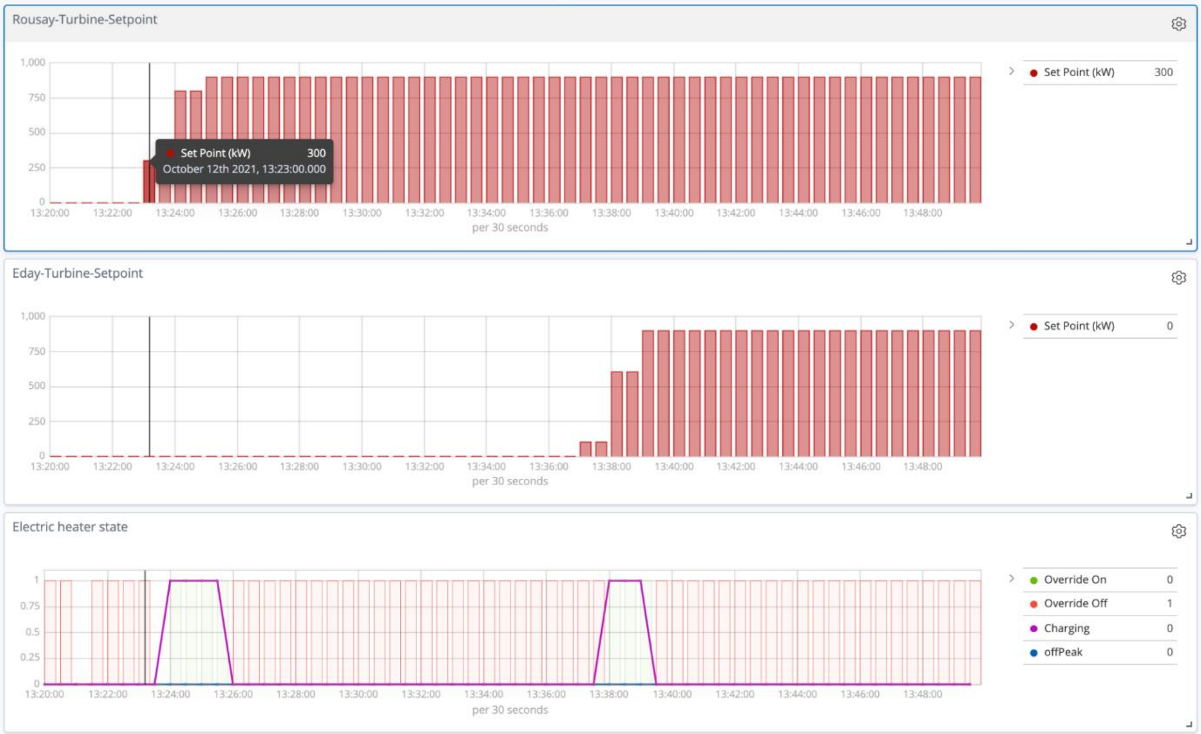


Figure 10: Type 1 response to curtailment event

From ~13:23-13:25, the Rousay turbine setpoint is between 0-900 kW (starting with an initial setpoint of 300 kW), indicating that Rousay is marginally curtailed. Soon after, the Sunamp unit is in "Override on" mode (green bars) based on Kaluza platform's instruction which results in charging of the heating elements and storage of energy in the supplementary storage (as indicated by the purple line). After 13:26, the Rousay turbine is once again uncurtailed (setpoint = 900 kW) and the platform instructs the Sunamp unit to be in "Override off" mode.

From ~13:37-13:39, it can be seen that the Eday turbine is emerging from a fully curtailed to a marginally curtailed state, finally moving to an uncurtailed state at ~13:40. During this time, again, the Sunamp unit is in "Override on" mode (green bars) based on the platform's instruction which results in charging of the heating elements and storage of energy in the supplementary storage (as indicated by the purple line). After 13:39, the platform instructs the Sunamp unit to be in "Override off" mode in response to Eday becoming uncurtailed.

3.2.3 Curtailment Effectiveness

By the end of the SMILE Orkney project in October 2021, six Type 1 systems were consistently in communication with the Kaluza platform, and we had seen a consistent response to both simulated and real wind turbine curtailment events from several of these systems. The system configuration was demonstrated to be effective as a means to absorb and reduce the need for wind turbine marginal curtailment.

Quantitative results on curtailment response for Type 1 systems are limited due to several issues discussed below (and among the others, as mentioned before, for a significant period in 2021, the Eday turbine was unavailable, due to Eday's two subsea power cables failing). However, a counterfactual analysis looking at the maximal output of all type 1 systems during 2021 indicates that these six systems could have delivered a total of **1,007 kWh from Jan '21 to Oct '21** had systems worked as expected. For an explanation of the methodology used, see the *Response Effectiveness: All System Types* section.

Installation of type 1 systems began in 2019, with work to allow systems to communicate with the Kaluza platform taking place concurrently. On completion, there were a number of difficulties in communicating with the installed systems. Communication failure due to unstable internet has been detected in several situations. In some cases, site visits and the installation of signal boosters was able to resolve these issues, but a number of systems continued to provide only partial data, and some failed to communicate at all.

Early in the project, where communication was possible, devices were found to be unresponsive to commands. An iterative process of development and testing between project partners was undertaken in an attempt to understand why systems which were otherwise communicating and functional were unable to provide a response to curtailment signals sent from the Kaluza platform. Additional tooling for real-time data capture, visualisation and monitoring - outside of the original scope of the project - was introduced to help project partners facilitate installation checks, on-site troubleshooting and deeper understanding of the interplay between firmware on the installed systems and the platform. The process continued throughout the project, and was accelerated with the development of a tool to dispatch 'simulated' turbine curtailment events, where no real events were taking place, in May 2021. Building these capabilities was particularly important to help project partners to collaborate and investigate issues remotely during Covid-19 induced lockdowns. This enabled much more rapid testing of any software or hardware changes, and was critical to the successful demonstration of this and other system types. Modifications to software and hardware configuration continued until August 2021 and eventually yielded success in the form of consistent response to curtailment signal seen throughout September and October.

3.2.3.1 Issues Affecting Curtailment Effectiveness

An issue which was found to impact the effectiveness of type 1 systems was difficulty in managing site visits during the pandemic. Deployments of updated device firmware required in-person access to a device, as did rectification of system wiring or adjustment of communications equipment. During lockdown periods in the UK this work was unable to take place, and as some level of restrictions have been in place almost consistently since March 2020 the development and feedback cycle was unfortunately slowed.

Damage to a subsea cable connecting the Eday turbine to the rest of the Orkney archipelago reduced the curtailment event volume massively for the first half of 2021 at a crucial stage for the demonstrator. While the cable was eventually repaired, limited access to real curtailment events during March and April 2021 compounded pandemic effects and made the system validation stage longer and more complicated.

While several systems were fully operational for the months of August, September and October 2021, this period coincided with a steep drop in marginal curtailment at either turbine (see results under All System Types for a view of total curtailment minutes).

3.2.4 Learnings

Bringing Type 1 systems online presented a number of challenges in addition to those given in the previous section. The heat storage systems in use, provided by Sunamp, were not designed originally to connect directly to the internet and required additional monitoring hardware to be added during the project (Kaluza platform connected gateway units). The integration of these two novel systems proved to be challenging, and monitoring and debugging the set-up remotely was very difficult in cases where device telemetry was missing or incomplete. There were occasions where site visits would have been the best option for troubleshooting, but this was made impossible by the pandemic.

While some of these problems were circumstantial, certain key learnings can be drawn from them.

The first of these is that when installing novel solutions, particularly where home heating is concerned, a long testing period in a controlled, workshop environment is preferable to earlier installation in real homes. While controlled testing did take place in the SMILE Orkney trial, home installations commenced early and with hindsight more time prior to installs could have been beneficial. That being said, it would have been difficult and expensive to faithfully replicate and validate before final physical installation, the various home configurations encountered over the course of the project.

Secondly, a high quality, consistent internet connection is a minimum requirement for most intelligent energy technologies. Poor quality internet connections are a real problem in remote areas of the UK, but for most purposes the source of connection issues is distance from routers or signal boosters. Lack of access to a working connection in the same room as equipment was being installed was responsible for a number of connection issues and a recommendation for similar future initiatives would be to make this a key eligibility criterion.

Finally, the communications and protocol issues between Sunamp and Kaluza controllers highlights a very strong case for onboard communications equipment in smart heating systems. Reliance on bespoke monitoring solutions adds an element of complexity and opportunity for installation error which can be removed if the primary controller is able to communicate remotely.

While less curtailment response was delivered than hoped, the systems brought online do however prove the concept that Sunamp heat batteries can play a role as system sink effectively, and given the challenges discussed above this should be considered a very positive result from a learning perspective and encourage future exploration of these technologies.

3.3 Type 2

3.3.1 System Configuration

The designed architecture for type 2 has similarities with type 1, through the use of Sunamp PCM heat batteries as the main form of energy storage. However, unlike type 1, types 2s use an Air to Water Heat Pump as the principle form of heat generation, rather than using the pre-existing heat source. To allow the type-2 system to be installed in a variety of properties with different existing heating systems three different type-2 sub-types were designed These three sub-types were: Type-2 Dual, Type-2 DHW (Domestic Hot Water), and Type-2 Space Heating. The different systems are outlined below in Figure 11, Figure 12 and Figure 13. After assessing properties to identify the most suitable sub-type, type-2 systems were installed in 13 properties.

For this installation, a Kaluza gateway unit enables communication between the Kaluza platform and the property's heating and hot water system. This utilised the homeowners own internet connection in order to facilitate communication links to the controller of the Sunamp heat battery (and indirectly to the ASHP).

The electricity demand of the install was determined by the size of the heat pump suitable for the property, and the rating of heating elements within the Sunamp PCM heat battery. The principle design called for installation of high temperature air to water Daikin Altherma heat pumps. This range of heat pumps have a thermal output of 11kW, 14kW and 16kW; with rated power inputs between ~4kW and ~6kW, respectively.

In comparison, the power demand of the Sunamp PCM heat battery is rated at approximately 2.8kW; this is the same power demand for the units available to the SMILE project. However, these units can be deployed in series with additional units to meet greater demand. As such, power demand could be 5.6kW, or even 8.4kW. The individual units can be suitably scaled in order to meet the specific requirements of participating households; principally dependent upon the daily demand on hot water. The scales of units that would be considered for this install configuration were 3, 6, 9 or 12kWh. The models are designed for internal deployment, and in many cases installed in under counter spaces. The four models all have the same footprint (370 x 575mm), but vary in height (410, 605, 815 and 1,025mm, respectively).

The illustrated schematics, below, detail the equipment and approximate connection points for the three subtypes with the Type 2 design:

Figure 11 details the Type 2 Dual installation type, which would provide the capacity to store thermal energy within the hot water and space heating hydraulic circuits; three batteries for the hot water and two for the space heating. Only one of the three PCM heat batteries on the hot water circuit was fitted with an electric heating element. This element was available for curtailment matching control. The purpose of the other two batteries was to meet the hot water needs of the property and were primarily charged by the ASHP according to a preconfigured schedule. As illustrated in Table 11, the hydraulic configuration was such that in the case of a curtailment event that resulted in the ASHP being overridden, all three HW batteries were charged. The two PCM batteries on the space heating circuit were designed to only be charged in response to an override command from the aggregator platform. Otherwise, the heat pump would heat the house directly, bypassing the heat batteries.

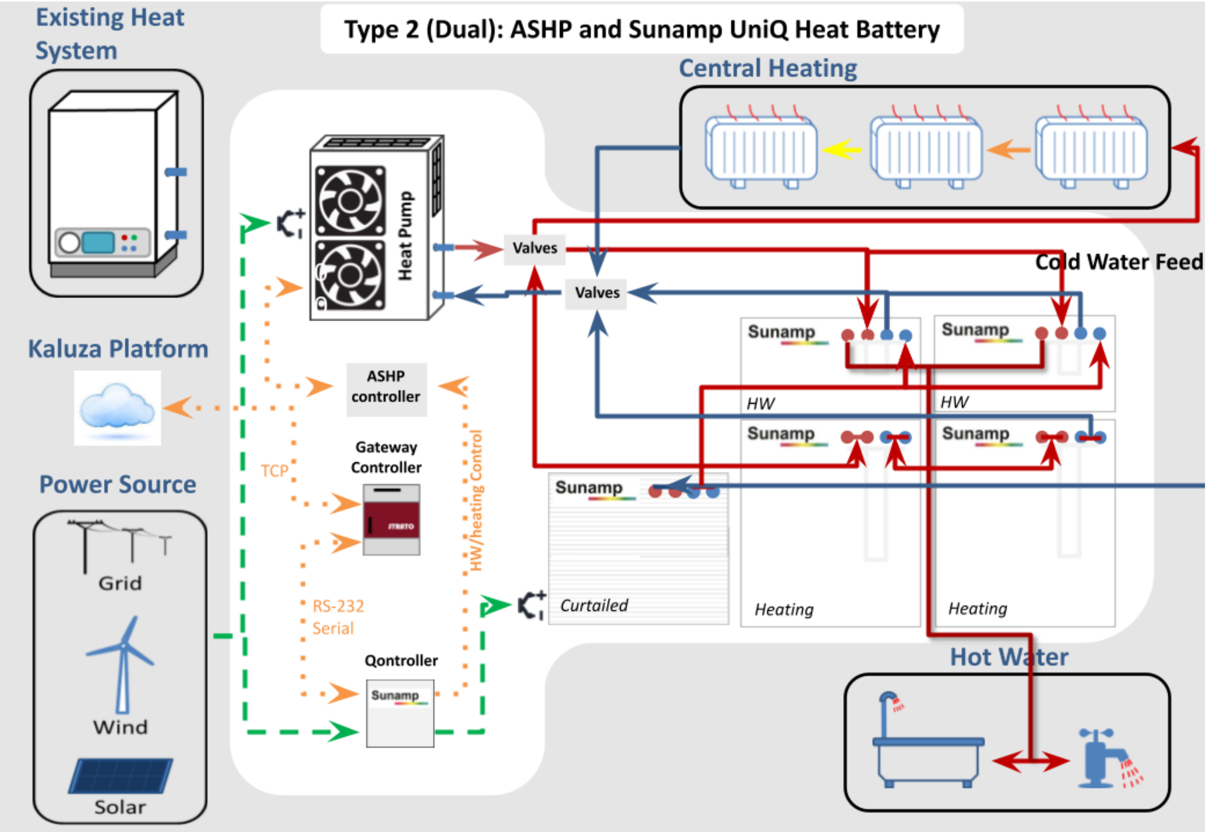


Figure 11: Type 2 system with dual storage for both central heating (CH) and domestic hot water (DHW)

Figure 12 details the schematic for the Type 2 DHW sub-type. This was the same installation of a heat pump, connected to only two PCM heat batteries. These heat batteries were only on the hot water circuit; there was no storage on the space heating circuit. This install was only completed when it was determined that it was not possible to fit enough batteries to meet the Type 2 Dual sub-type design. In the Type 2 DHW configuration, both heat batteries were able to be overridden by the Kaluza platform in response to curtailment events but in different ways: one with an internal heating element which was able to react immediately; and the other as a result of overriding the ASHP to complement any energy already stored in the main heat battery. The heat pump would always heat the house directly as there was not provision for storage on the space heating circuit.

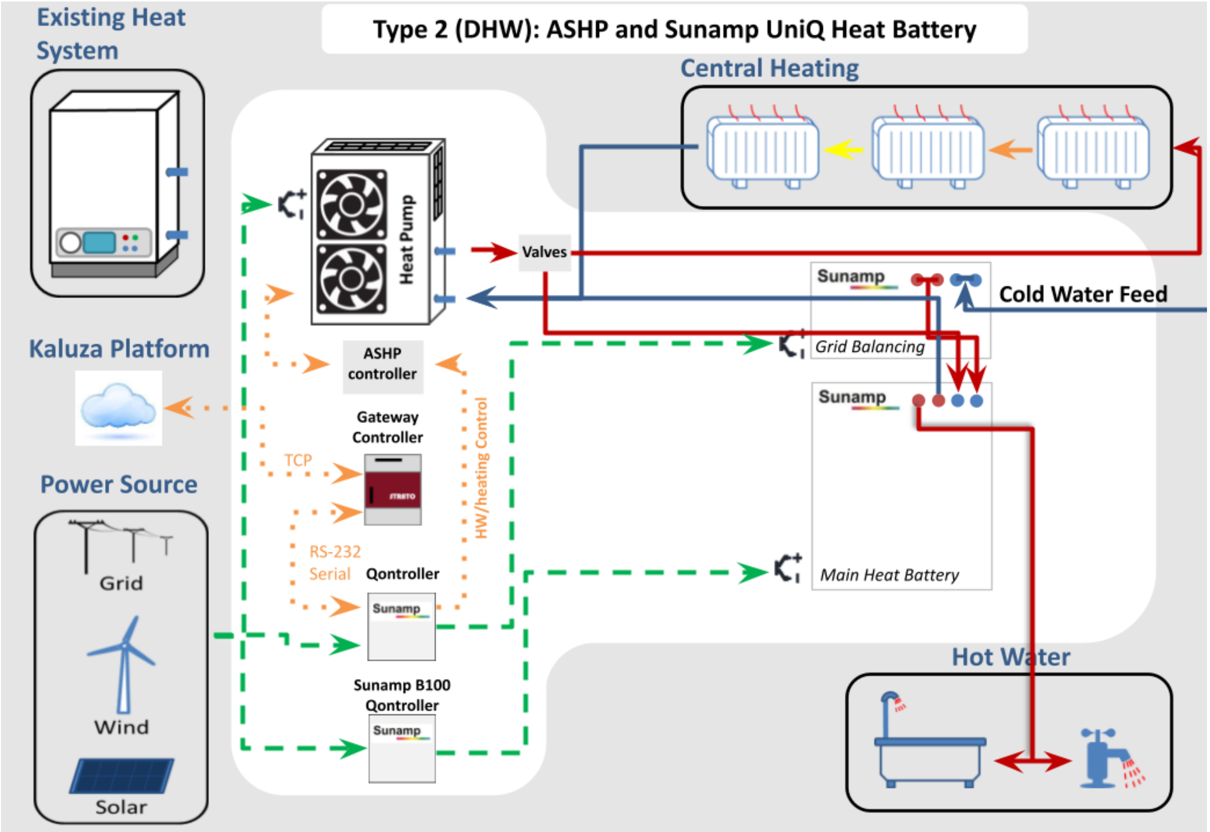


Figure 12: Type 2 system with storage for DHW only

Figure 13 details the configuration of the Type 2 Space Heating sub-type. This installation was solely able to store thermal energy on the space heating circuit. The heat pump had no requirement to deliver hot water for the property. This was only installed in a single property in response to the contractors determining it was not possible to complete a full Type 2 Dual installation due to the construction method for the property itself.

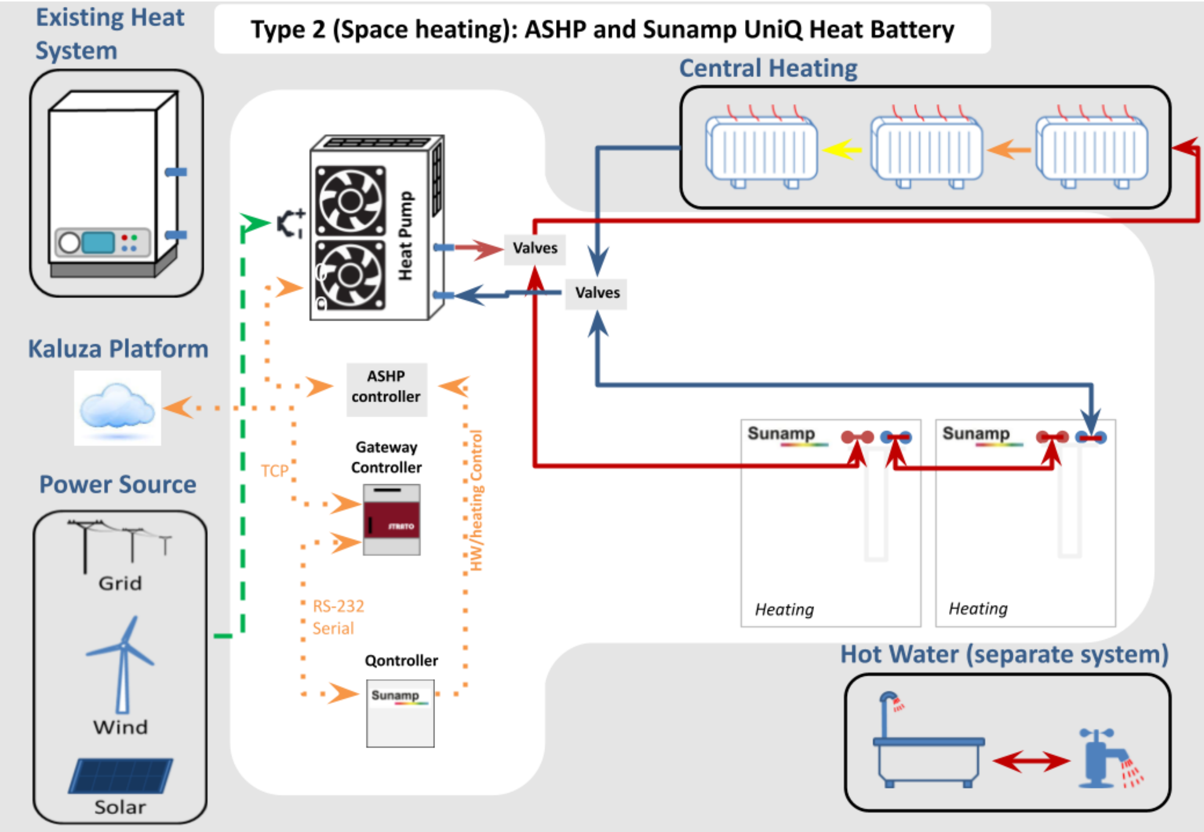


Figure 13: Type 2 system with storage for CH only

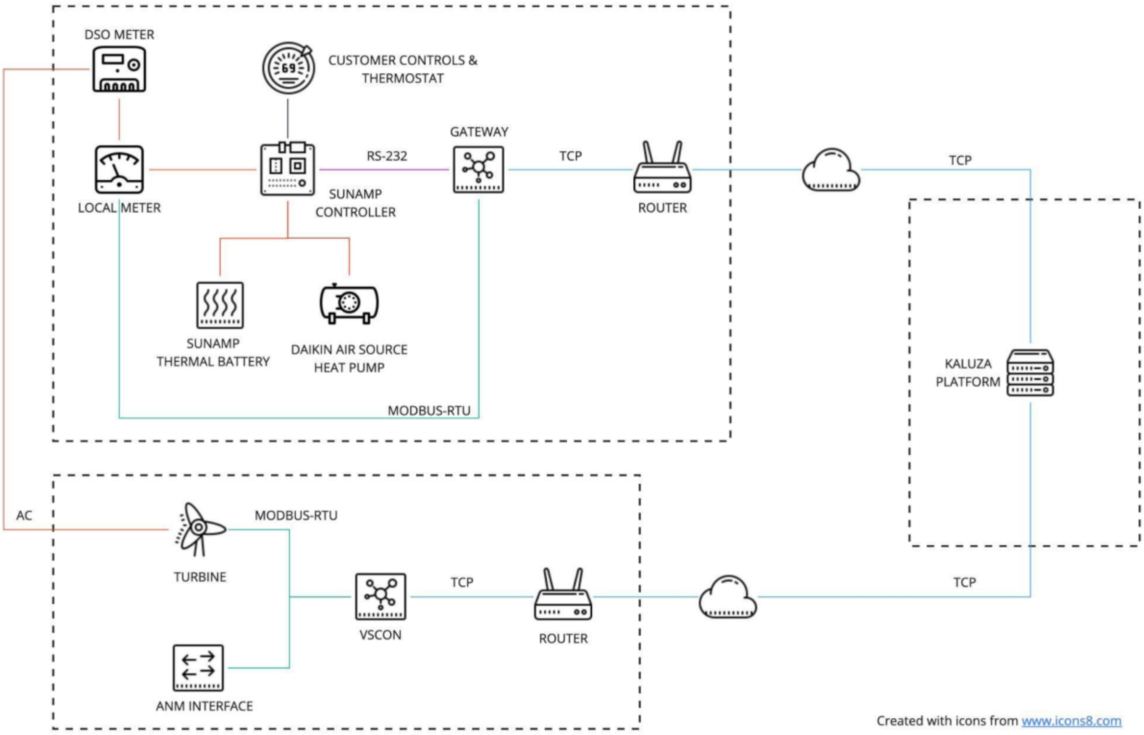


Figure 14: Type 2 control and integration configuration

Figure 14 illustrates the end to end control integration between the Type 2 on-site installation, the wind turbines and the Kaluza platform. The functionality and connectivity of each component is described in Table 3.

Table 3: Components and functionality of the Type 2 system

Component	Description/Specification	Connectivity	Location
VSCON	The VSCON unit monitors for, and transmits curtailment information from the wind turbine and the local smart grid (ANM interface).	Modbus-RTU/TCP from the wind turbine and ANM interface. Ethernet (TCP) to onsite router.	Wind Turbine
Kaluza Platform	Cloud-base control aggregator responsible for the smart functionality controlling of all equipment (either directly or indirectly), on both the generation and demand side of the SMILE infrastructure.	TCP connection over the public internet between internet routers located at wind farms and customer homes.	Kaluza Data Centre
Kaluza Gateway	The Kaluza Gateway provides on-site control of equipment by relaying information from the Kaluza platform, and also returning data back again for processing.	Ethernet (TCP) from onsite router, and RS-232 serial link to the Sunamp controller.	Customer's Home
Sunamp Controller	Controller unit dedicated to the control and monitoring of Sunamp PCM heat battery. In this configuration, the controller acts as the conduit between Kaluza platform's control signals and the charge/discharge control of the PCM heat batteries.	Controlled by the Kaluza Gateway unit via RS-232 serial bus.	Customer's Home
Sunamp PCM Heat Battery	Stores thermal energy. Scaled to required size in 2.8kW units, with storage capacities of 3, 6, 9 and	Controlled by Sunamp Controller via RS-232.	Customer's Home

	12kWh. Thermal energy stored in Phase Change Material solutions in sealed blocks. Heat exchangers transfer either heat to or from water flowing through the battery depending on charging or discharging.		
Air Source Heat Pump	Principal source of heat. Daikin Altherma high temperature split block unit with a rated power input between 4kW and 6kW, and a rated output between 11 and 16kW, respectively.	Direct plumbed closed-loop hot water loop. Comms link between Sunamp controller and Daikin ASHP controller.	Customer's Home
Daikin Controller	Daikin controller provides control of the ASHP by responding to data transmitted from rhw Kaluza platform. The controller will also process data from the hot water storage and signal the ASHP and hot water pumps accordingly.	Modbus-RTU comms connection between the Daikin controller and Daikin ASHP.	Customer's Home
Local meter	A 100A power meter installed in the consumer unit to measure the power consumption of the SMILE-specific heating components	MODBUS-RTU to the Kaluza gateway	Customer's Home

The specific Type 2 configurations installed during the project are listed in Table 4.

Table 4: Quantity and type of Type 2 systems installed

Type 2 Configuration	Number of properties installed
Type 2 (Dual)	7
Type 2 (DHW)	5
Type 2 (Space heating)	1

3.3.2 Curtailment Operation

At a high level the curtailment mitigation system using Type 2 can be described as follows:

- Energy delivered through the heat pump is stored separately ("primary storage") from the energy delivered through the battery's internal electrically powered heating elements ("supplementary storage")
- The curtailment mitigation system does not interact with the primary storage and only interacts with the supplementary storage. Primary storage is managed purely based on a timer schedule as determined by the resident and the installer, and supplementary storage is purely managed by Kaluza platform's curtailment mitigation system
- When a turbine is marginally curtailed ("curtailment event"), the platform instructs the battery's internal electrically powered heating elements to turn on ("override on" mode) so as to deliver energy to the supplementary storage - so long as the curtailment event occurs during the off-peak window of the resident's energy tariff.

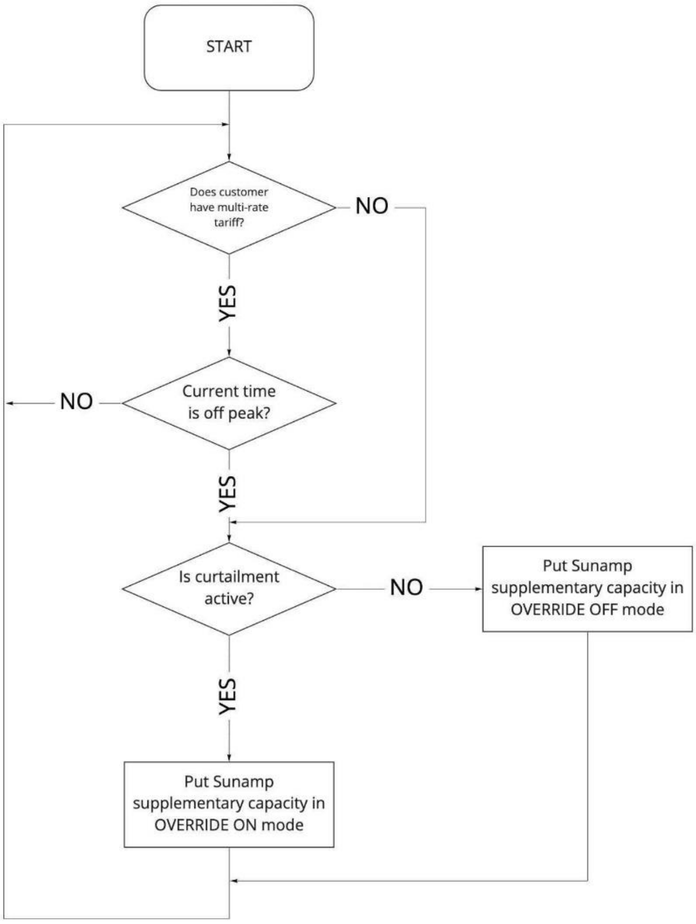


Figure 15: Type 2 control algorithm

Figure 16 below illustrates a curtailment event at the Rousay turbine and a Sunamp heat battery's response to it. As seen in the upper chart, at around 00:04 the turbine is uncurtailed with a setpoint of 900 kW. During this time, the Sunamp unit is in "Override off" mode, as seen in the lower chart.

Figure 16: Type 2 response to curtailment event

At around 00:20, the turbine setpoint is 0 kW - the Sunamp unit continues in "Override off" mode. At around 00:41, the turbine setpoint moves from 0 to 365 kW indicating that it is marginally curtailed, and it mostly continues in that state until around 01:05. During that period the Sunamp unit is in "Override on" mode (green bars) based on Kaluza platform's instruction which results in charging of the heating elements and storage of energy in the supplementary storage (as indicated by the purple line). After 01:05, the turbine is once again fully curtailed and the platform instructs the Sunamp unit to be in "Override off" mode.

As seen in the other time periods in the timeline above until 04:40, the Sunamp units are in "Override mode" and the heating elements are charging only when the turbine is marginally curtailed.

3.3.3 Curtailment Effectiveness

Type 2 system shared a similar control process with type 1, and was similarly demonstrated to be effective as a means to absorb and reduce the need for wind turbine curtailment. Throughout the measurement phase of the project, the number of type 2 systems delivering curtailment mitigation increased and eventually stood at six at the time of the project's conclusion.

Between 1st January and 31st October 2021, analysis of power data indicates that a total of **101 kWh** of curtailment mitigation was delivered by type 2 systems. This under-reports the true power delivered, however, as several of the installed power meters were found to have been wired incorrectly. Looking instead at the responses sent from Sunamp heater elements confirms that the true response was significantly greater at **257 kWh**.

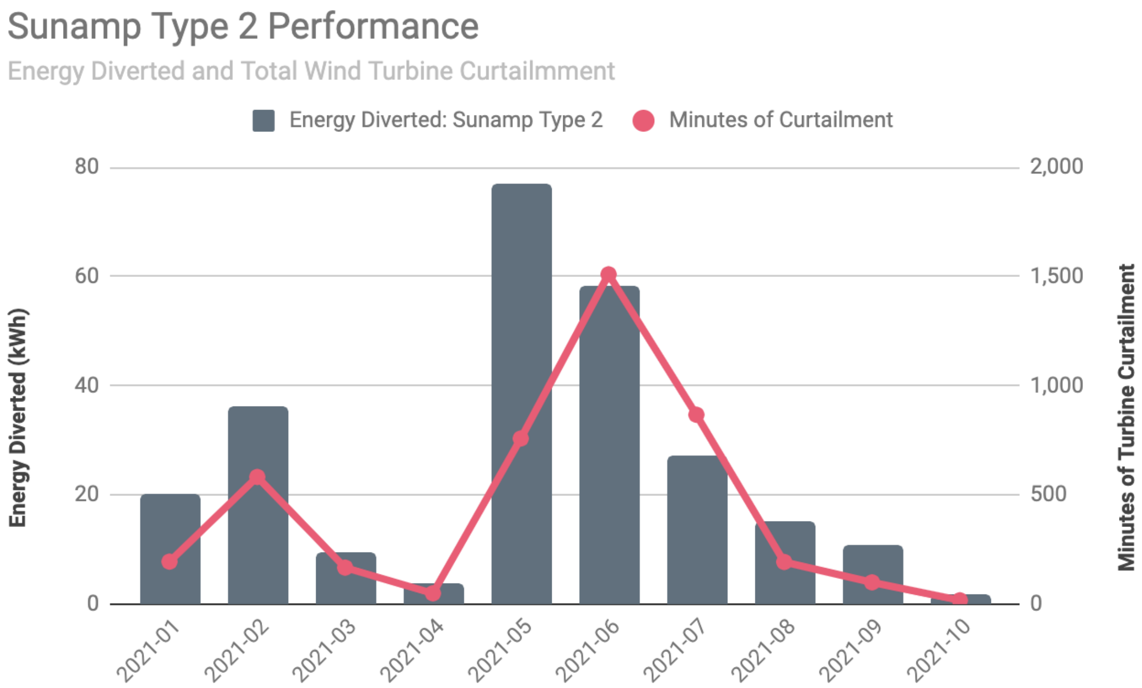


Figure 17: Curtailment and Type 2 Response

As with the type 1 systems, a counterfactual analysis was also conducted to determine the maximum possible energy that could have been diverted during curtailment events had all systems been fully operational. Over the same period of time, this figure was **1,303 kWh.**

This figure represents the theoretical maximum, but in reality could never have been attained, as it assumes instant dispatch and power ramp-up is possible. In reality, as the majority of curtailment events had a duration of less than two minutes and there is a natural lag in communication systems and onboard device software, the true maximum would have been significantly lower.

Control of a type 2 system was first achieved in November 2020 after delays to installation due to the increased design time required to develop the three different subtypes detailed in the earlier 'System Configuration' section. Throughout 2021 the number of systems responding to calls increased steadily as repairs were conducted and site-, and type-specific installation issues were ironed out. As with type 1 systems, the rate of improvement was slowed by pandemic restrictions. By the end of the project, of the thirteen total installations, six were regularly providing a response to wind turbine curtailment.

As with type 1, additional tooling for real-time data capture, visualisation and monitoring - outside of the original scope of the project - was introduced to help project partners facilitate installation checks, on-site troubleshooting and to facilitate deeper understanding of the interplay between firmware on the installed systems and the platform. The process continued throughout the project, and was accelerated with the development of a tool to dispatch 'simulated' turbine curtailment events where no real events were taking place. Building these capabilities was particularly important to help project partners to collaborate and investigate issues remotely during Covid-19 induced lockdowns.

3.3.3.1 Issues Affecting Curtailment Effectiveness

Issues affecting type 2 installation and troubleshooting were very similar to those affecting type 1. One particular problem which was identified late in the project (July 2021) was that several power meters were incorrectly wired to exclude power used to heat the Sunamp batteries directly, instead metering the heat pump only. This resulted in an artificially deflated curtailment response total when assessed in kWh terms. As we have been able to identify systems impacted cases in which 2.8 kW power was in fact diverted to the heater element, results have been corrected.

Pandemic restrictions were responsible for the inability to access and fix several systems with known issues, as arrangements were not always possible to safely revisit installs. The damaged subsea cable restricting access to the Eday turbine had a more substantial impact to the results for type 2 than type 1, as many type 2 systems were fully operational during the outage.

3.3.4 Learnings

As many of the learnings generated from working with type 2 systems are similar or identical to those of type 1 only challenges and insights specific to type 2 will be discussed here. Please refer to the Type 1 Learnings section for more general commentary.

The significantly greater degree of success in setup of type 2 systems compared to type 1 is notable. As mentioned, the protocols used and system software differed. Some speculations as to why the differences between these setups yielded such variance in outcomes are offered, with further investigation warranted.

As type 2 systems included an air source heat pump as well as the direct heating element, one battery was able to be dedicated entirely to curtailment response, and the role of heating element was restricted to this use only. This separation between ‘primary’ storage batteries and ‘supplementary’ storage batteries made working with communications protocols of the controller simpler, and separated the twin tasks of the Sunamp controller (managing heat pump operation and controlling the curtailment battery).

Operation of the heat pump in the Type 2 Dual and Type 2 Space heating subtypes was proven to be relatively ineffective to respond to curtailment events. The time required to ramp up the heat pump and begin charging the space heating Sunamp PCM heat batteries was significantly greater than the typical marginal curtailment events. This approach was not focused on any further testing and available development was completed. Focus remained solely on the significantly more effective control of electrical heated PCM heat batteries.

While this system type brought simplifications in operational terms, the cost was that supplementary storage was underutilised, only being called upon during relatively rare wind turbine curtailment events. While we are satisfied that once again the Sunamp system was demonstrated to be able to divert energy during curtailment, the capital cost of such a system would require far greater utilisation to be cost effective. As such, a commercial deployment would almost certainly require a solution in which primary and supplementary (flexible) storage was shared across the same devices.

3.4 Type 3

3.4.1 System Configuration

The configuration for type 3 paired an Air to Water Heat Pump with hot water storage; similar to type 2 but testing the effectiveness of hot water storage in comparison to Sunamp PCM heat batteries. As with the type 2s, different subtypes of the type 3 system were designed to test hot water storage in the hot water storage tank only (Type 3 DWH), as well as using additional hot water storage in a space heating storage tank (otherwise referred to as a 'buffer' tank) (Type 3 Dual). Unfortunately, an early trial of a space heating storage tank was unsuccessful and further investigation revealed some inconsistencies between design assumptions and the as installed systems. Hence, despite significant effort by the partners to design an effective end to end system, no Type 3 Dual systems were installed. This configuration for the Type 3 DWH, or an amended version of, was installed in 10 properties and outlined below in Figure 18 and **Figure 19**.

The electricity demand of the install was determined by the size of the heat pump suitable for the property, and the rating of immersion element(s) of the hot water cylinder. The scale of these and that of the energy storage was based on the properties requirements as per **Table 5**.

The principle design called for installation of high temperature air to water Daikin Altherma heat pumps. Typical installs had a thermal output between 11kW and 16kW; with rated power inputs of between 4kW and 6kW, respectively.

The chosen hot water cylinders for this installation type were from the Megaflo range manufactured by Heatrae Sadia. This is an unvented and indirect hot water cylinder, equipped with a bottom 3kW immersion element in every model, with some also fitted with a 3kW top immersion element.

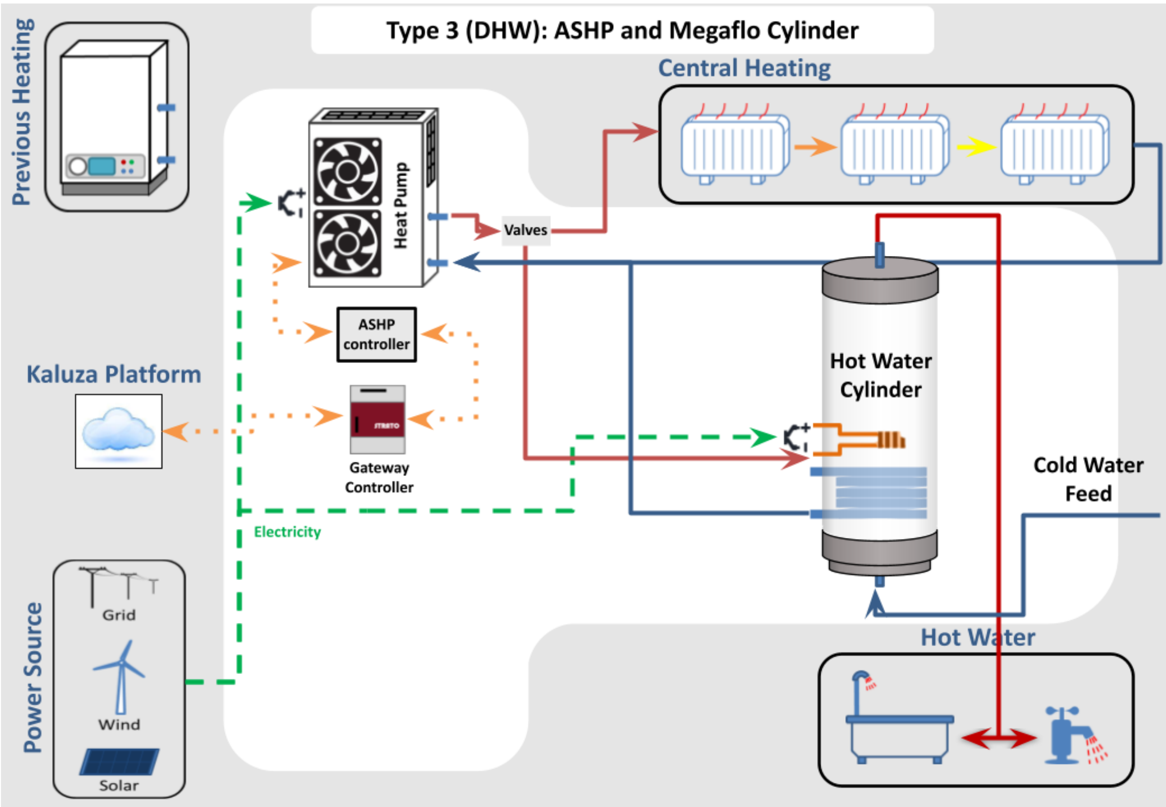


Figure 18: Type 3 system configuration

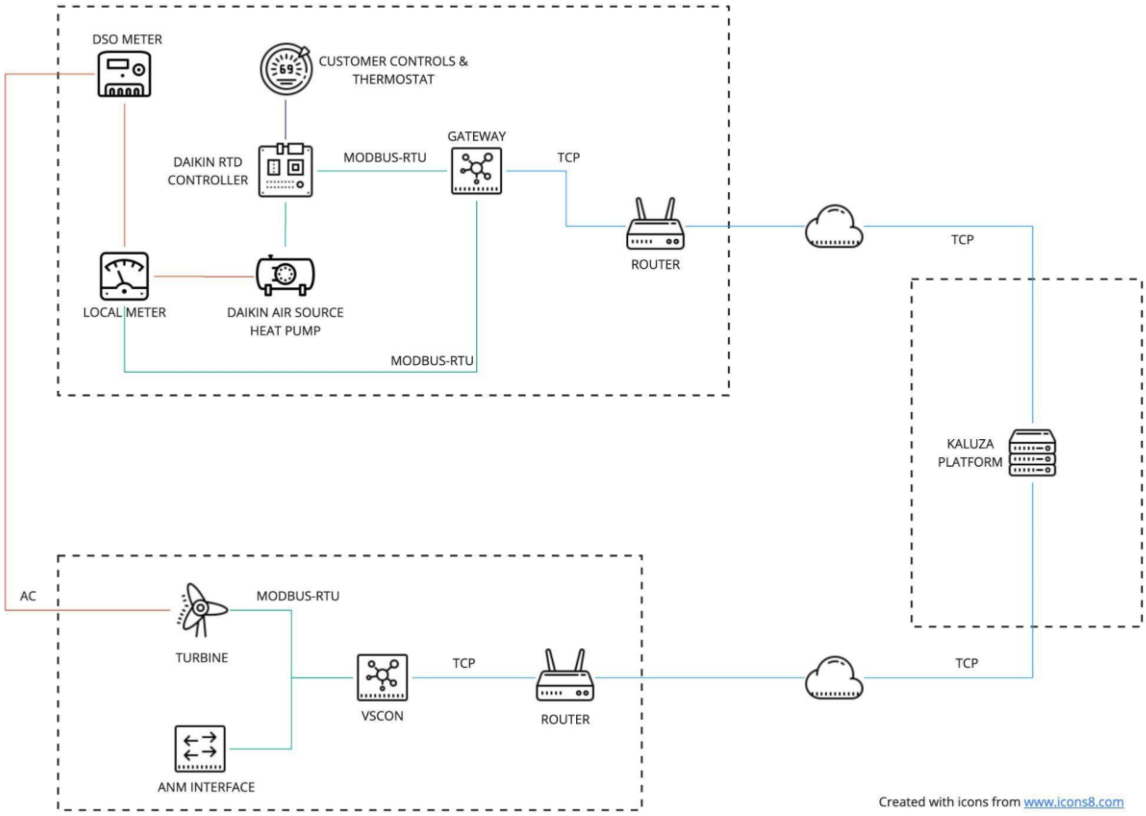


Figure 19: Type 3 control and integration configuration

Table 5: Components and functionality of the Type 3 system

Component	Description/Specification	Connectivity	Location
VSCON	The VSCON unit monitors for, and transmits curtailment information from the wind turbine and the local smart grid (ANM interface).	Modbus-RTU/TCP from the wind turbine and ANM interface. Ethernet (TCP) to onsite router.	Wind Turbine
Kaluza Platform	Cloud-base control aggregator responsible for the smart functionality controlling of all equipment (either directly or indirectly), on both the generation and demand side of the SMILE infrastructure.	TCP connection over the public internet between internet routers located at wind farm and customer's home.	Kaluza Data Centre
Kaluza Gateway	The Kaluza Gateway provides on-site control of equipment by relaying information from the Kaluza platform, and also returning data back again for processing.	Ethernet (TCP) from onsite router to MODBUS-RTU interface on the Daikin RTD-W Controller.	Customer's Home
Hot Water Cylinder (Heatrae Sadia Megaflo, or equivalent)	Hot water storage typically ranges in capacity between 100 and 300L. Heated in-directly from ASHP. Each cylinder, depending on the model with either have a single or double immersion element; each equating to a power consumption of 3kW. High level of inbuilt insulation provides lower levels of heat loss in comparison to conventional hot water cylinders. Will supply hot water to taps, showers and baths.	Plumbed closed-loop hot water connection with ASHP	Customer's Home
Air Source Heat Pump	Principal source of heat. Daikin Altherma high temperature split block	MODBUS-RTU connection interface for control by	Customer's Home

	unit with a rated power input between 4kW and 6kW, and a rated output between 11 and 16kW, respectively.	Gateway and Daikin Controller	
Daikin Controller	Daikin controller provides control of the ASHP by responding to data transmitted from rhw Kaluza platform. The controller will also process data from the hot water storage and signal the ASHP and hot water pumps accordingly.	Modbus-RTU comms connection between the Daikin controller and Daikin ASHP.	Customer's Home
Local meter	A 100A power meter installed in the consumer unit to measure the power consumption of the SMILE-specific heating components	MODBUS-RTU to the Kaluza gateway	Customer's Home

The specific Type 3 configurations installed during the project are listed Table 6.

Table 6: Quantity and type of Type 3 systems installed

Type 3 Configuration	Number of properties installed
Type 3 ASHP and DHW Cylinder	10

3.4.2 Curtailment Operation

The original control design of the type 3 system planned to control the curtailment dispatch by remote control using the ASHP in-built controls. After an unsuccessful trial of a type 3 Dual system, an in-depth review of the local set-up and ASHP in-built control capabilities revealed that the original control design could not provide the required curtailment dispatch control for either of the type 3 sub-types. An iterative development process between partners and the installation contractors produced a new control design which, at a high level, split the control system into components of both local and remote control, and the local system was adapted to include a 'curtailment dispatch' control loop in addition to the 'standard operation' control loop.

The standard operation loop of the local control system was designed to manage the residence's heating requirements to guarantee the primary need in terms of comfort (i.e. temperature) is maintained, even in the absence of an internet connection to the Kaluza platform. The standard operation would handle **scheduled** charging of the hot water storage tanks within the constraints of the occupant's energy tariff.

In the event of a curtailment event, the remote control system was designed to send a signal to activate the 'curtailment dispatch' control loop of the local control system. The local control system would then assess the capacity of the storage tanks and switch on and direct hot water to the storage tank with capacity.
The overall algorithm is illustrated in the flowchart in Figure 20.

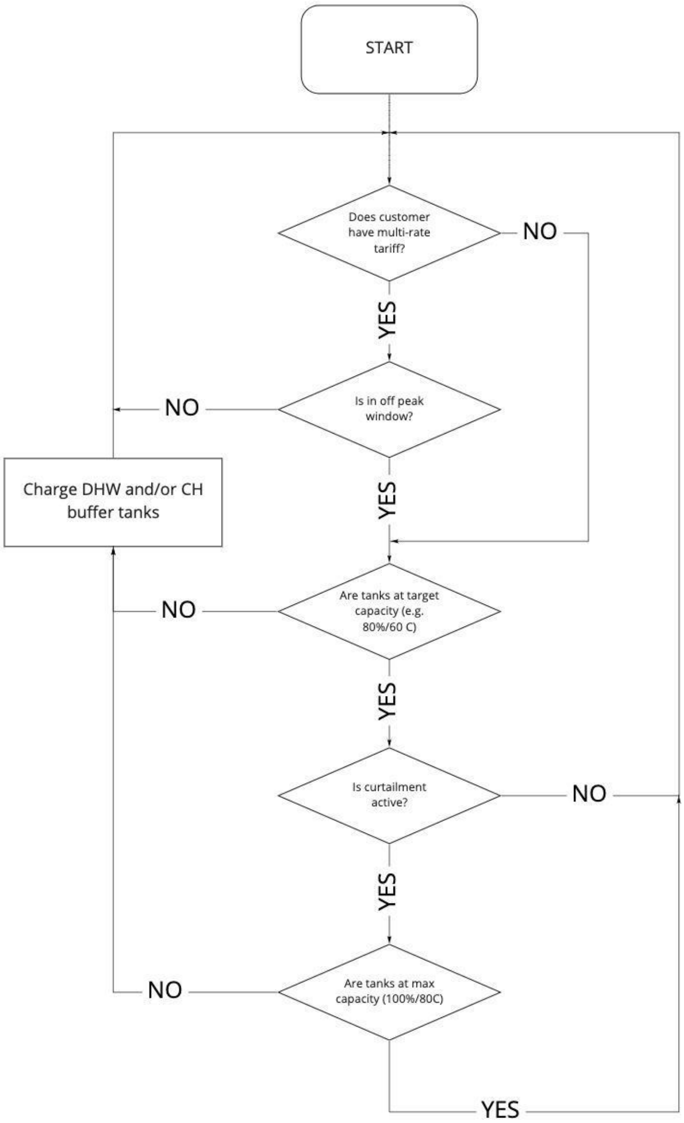


Figure 20: Type 3 control algorithm flowchart

As illustrated by Figure 20, under 'standard operation', the local control system charges the appropriate tanks to a target state of charge (i.e. a specific tank temperature) in order to meet the occupant's primary daily energy requirements. The systems were sized in such a way that the target state of charge is sufficient to meet the occupant's daily energy requirements with additional headroom in the system to capture additional heat generated by the heat pump as a result of a curtailment event. Consequently, curtailment events cause the heat pump to run in the event that the relevant tanks are at below their maximum state of charge, and the time of the curtailment falls within any off-peak tariff constraints (where applicable).

Figure 21: Curtailment events and heat pump response in Type 3 system

Figure 21 above, illustrates a number of curtailment events that were dispatched to the heat pump in the Type 3 DHW trial system (in the installation contractor's workshop), under one of the earlier control re-design iterations. This accounts for the fact that the flow and return temperatures are below the set point, as this particular heat pump is directly coupled to a radiator network instead of buffer/hot water tanks. Under this iteration the remote control system communicated directly with the ASHP to override the local system and turn the ASHP on during curtailment events. This design iteration was not possible as there proved to be a number of challenges with coordinating the ASHP turning on with the local hydraulic installations, in particular with the capability to divert hot water between the space heating system, and the storage tanks.

3.4.3 Curtailment Effectiveness

Significant efforts were made to develop an effective control system for type 3 systems. Whilst it was not possible to demonstrate the effective dispatch of curtailment to the full system, through development it was possible to demonstrate the potential to send an override signal to the ASHP when wind turbine curtailment took place. An example of successful dispatch of the heat pump is illustrated in the previous section, making use of the test system installed in the RS Merrimans workshop. This iteration of the control system was trialled in early May 2021

Unfortunately, by the time the final control design had been completed there was insufficient time remaining in the project to implement the final control design which required significant upgrades to the existing local control system. As such, type 3 systems never contributed to the diversion of energy during real wind turbine curtailment events, and no quantitative results were obtained.

The tests discussed offered a demonstration of the concept of an air source heat pump and hot water cylinder system operating flexibly and absorbing otherwise wasted renewable electricity.

3.4.4 Learnings

The challenges relating to the installation and operation of this system type were extensive. Issues were found with the original control design which could not be supported by the existing hydraulic, and electronic control system design, at this stage already installed in all participating properties. This required an iterative redevelopment of the communication and control systems which required the intensive consultation of the installation contractor as well as remote collaboration between contract partners. This redevelopment was hampered by pandemic restrictions limiting access to the test rig and properties to confirm the as installed reality of the local system and demonstrate and implement the required intermediate controls tests. Therefore, by the time a final control design was arrived at there was insufficient time to implement the required physical changes, and the decision was taken to suspend development work on this system type.

The learnings from working with type 3 systems are valuable, and indicative of the challenges of implementing novel heating and cooling systems. Recommendations for future initiatives echoes comments in the Type 1 section, with a strong emphasis on pre-testing in controlled environments, along with attempting to keep physical and control system development in lockstep to enable continuous validation and earlier error detection. While there was the benefit of a test system on Orkney, it did not fully simulate the system as it would appear in participants' homes, and with only remote access to the system possible a full set of scenarios could not be tested using Kaluza platform control. Heating systems generally have to be adapted to each home in which they are installed, often with the inclusion of legacy pipework. This adds complexity to the process and necessitates a variety of test scenarios prior to implementation.

Another insight which is shared between all heating system types is that onboard communications as opposed to external hardware control systems will make control of such systems easier and safer for consumers. The risk of imposing external controls on a heating system is that any error could lead to the loss of heating for a system user; a risk which must absolutely be minimised given the seriousness of outcomes associated with lack of heating and hot water in the home. It is noted that in more recent versions of the Altherma heat pump, Daikin now supports internet connectivity, meaning that in future it is anticipated that control can be mastered by a single controller while receiving external commands.

Air source heat pump systems offer significant potential for flexibility, but the greatest care must be taken to avoid the risk of restricting access to heat and hot water. Control of heat pump based systems requires extensive testing in a diverse set of scenarios beyond that which could be achieved with a single workshop installation. As interest in heat pumps develops worldwide, further initiatives seeking to utilise this technology to offer flexibility to power grids as well as reduce the carbon impact of home heating must surely be undertaken.

3.5 Type 4

3.5.1 System Configuration

The type 4 installation (Figure 22 and Figure 23) further builds upon the type 3 installation, with the use and benefits of electrical storage, air to water heat pumps and hot water storage. With the exception of the stationary electrical battery, the type 4 installation is the same as that of type 3. The battery further enables quick response to curtailment signals.
The electricity demand of the install was determined by the battery's rated power and the size of the heat pump suitable for the property. The Battery Energy Storage System (BESS) provided by Lithium Balance, consisted of a Xolta battery bank, rated at 7.5kWh (usable energy) and Victron Energy power inverter, within a rated power of 3.6kW. This battery was dedicated to matching the power demand of the ASHP; however the ASHP would regularly exceed the maximum power of the BESS, resulting in a shaving of power peaks rather than meeting 100% of the power requirements. The battery itself has a data connection to the Lithium Balance Data Centre, via the customer's home's internet router, in order to provide remote monitoring and management.
The principle design calls for installation of high temperature air to water Daikin Altherma heat pumps. Typical installs have a thermal output between 11kW and 16kW; with rated power inputs of between 4kW and 6kW, respectively.

Description of Lithium Balance management system: power meter, gateway in Battery, API to Kaluza.

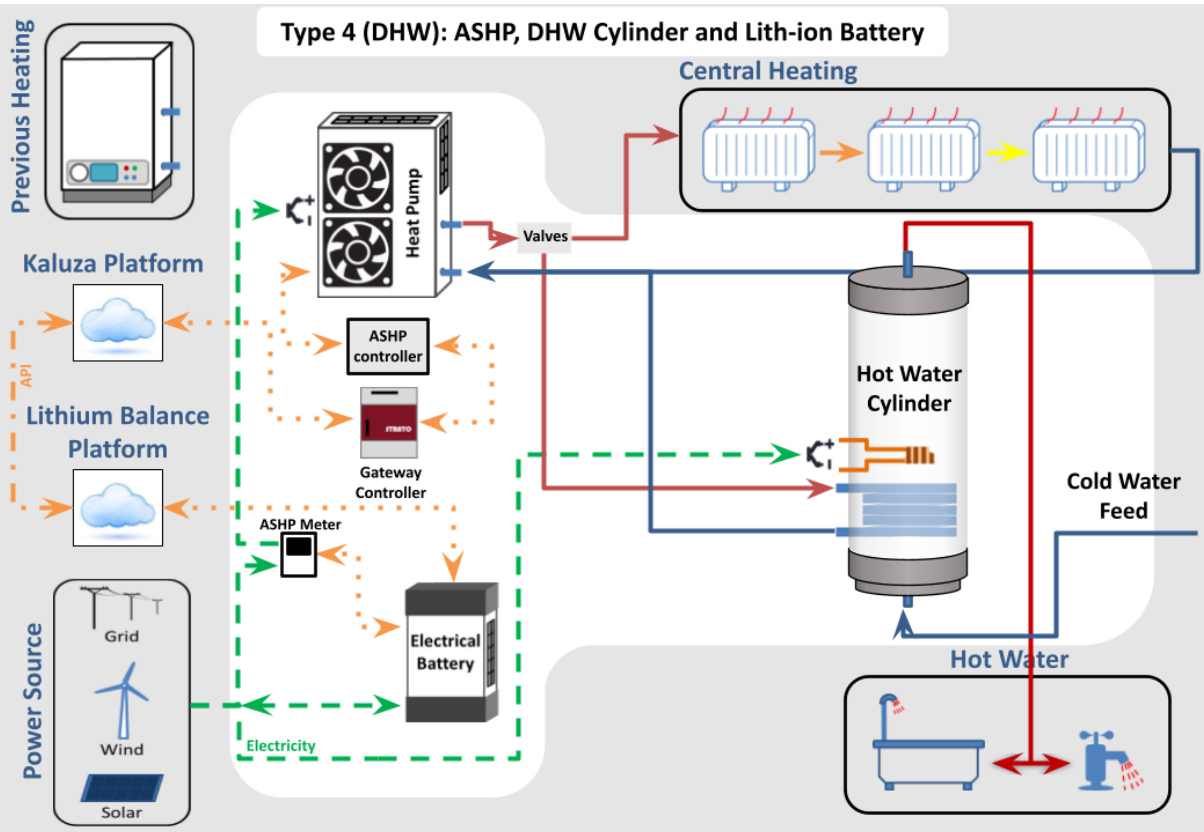


Figure 22: Type 4 system configuration

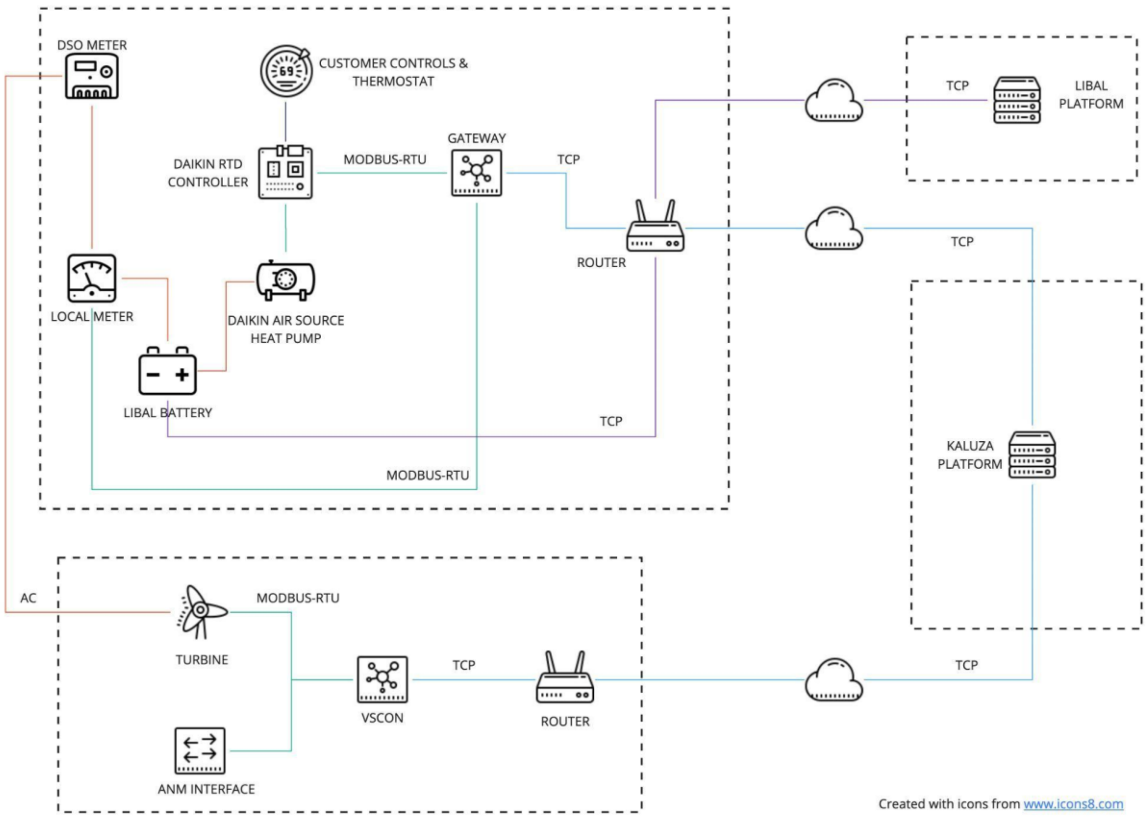


Figure 23: Type 4 control and integration configuration

Table 7: Components and functionality of the Type 4 system

Component	Description/Specification	Connectivity	Location
VSCON	The VSCON unit monitors for, and transmits curtailment information from the wind turbine and the local smart grid (ANM interface).	Modbus-RTU/TCP from the wind turbine and ANM interface. Ethernet (TCP) to onsite router.	Wind Turbine
LiBal Platform	To provide remote control of charging/discharging events of lithium-ion battery, while also acting as remote monitoring.	TCP internet link between the Lithium Balance platform and the customer's home's internet router	Lithium Balance Data Centre
Kaluza Platform	Cloud-base control aggregator responsible for the smart functionality controlling of all equipment (either	TCP connection over the public internet between internet routers located at wind farms and	Kaluza Data Centre

	directly or indirectly), on both the generation and demand side of the SMILE infrastructure.	customer's home.	
Kaluza Gateway	The Kaluza Gateway provides on-site control of equipment by relaying information from the Kaluza platform, and also returning data back again for processing.	Ethernet (TCP) from onsite router to MODBUS-RTU interface on the Daikin RTD-W Controller.	Customer's Home
Hot Water Cylinder (Heatrae Sadia Megaflo, or equivalent)	Hot water storage typically ranges in capacity between 100 and 300L. Heated in-directly from ASHP. Each cylinder, depending on the model either has a single or double immersion element; each equating to a power consumption of 3kW. High level of inbuilt insulation provides lower levels of heat loss in comparison to conventional hot water cylinders. Will supply hot water to taps, showers and baths.	Plumbed closed-loop hot water connection with ASHP	Customer's Home
Air Source Heat Pump	Principal source of heat. Daikin Altherma high temperature split block unit with a rated power input between 4kW and 6kW, and a rated output between 11 and 16kW, respectively.	MODBUS-RTU connection interface for control by Gateway and Daikin Controller	Customer's Home
Daikin Controller	Daikin controller provides control of the ASHP by responding to data transmitted from rhw Kaluza platform. The controller will also process data from the hot water storage and	Modbus-RTU comms connection between the Daikin controller and Daikin ASHP.	Customer's Home

	signal the ASHP and hot water pumps accordingly.		
Local meter	A 100A power meter installed in the consumer unit to measure the power consumption of the SMILE-specific heating components	MODBUS-RTU to the Kaluza gateway	Customer's Home
Lithium Balance Lithium-ion Battery (BESS)	3.6kW/ 7.5kWh (usable energy) battery. This monitors and matches the instantaneous power demand of the ASHP to reduce the net power demand to zero until discharged. The aim of which is to charge the battery during times of curtailment to allow the ASHP to operate consuming otherwise curtailed energy before importing from the grid	Connected to the Lithium Balance data centre via the customer's home's internet router	Customer's Home

The specific Type 4 configurations installed during the project are listed in Table 8.

Table 8: Quantity and type of Type 4 systems installed

Type 4 Configuration	Number of properties installed
Type 4 ASHP + electrical battery systems	5

3.5.2 Curtailment Operation

At a high level the battery is configured to discharge to meet the electricity consumption of the ASHP by means of a power meter measuring the real-time power consumption of the ASHP. This means that any energy stored in the Lithium Balance electrical battery is only used when the ASHP is running, and will be used before any electricity is imported to the premises from the grid.

The Type 4 installation algorithm operates as illustrated by the flow chart in Figure 24.

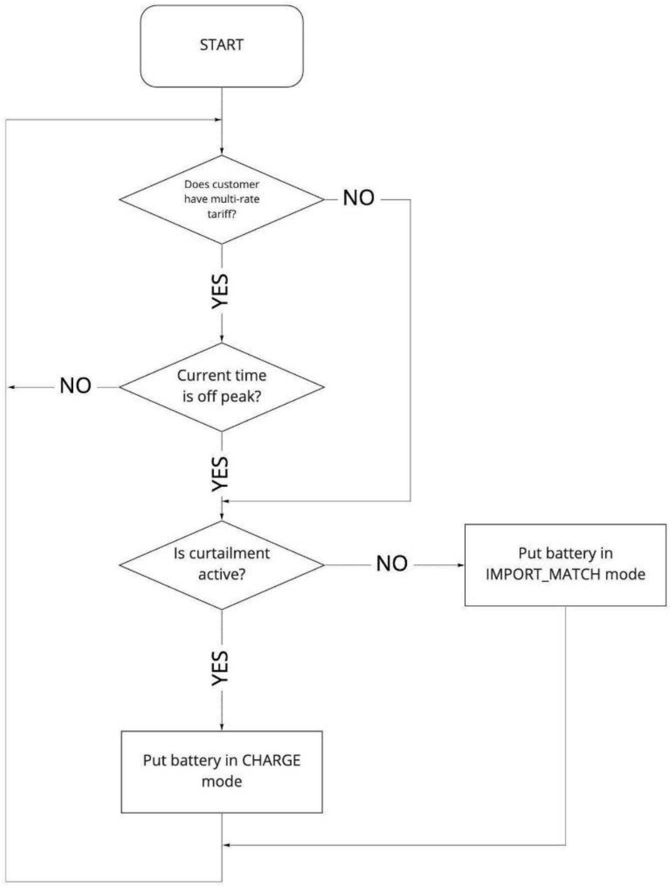


Figure 24: Type 4 control algorithm flow chart

Essentially, within the tariff constraints of the resident, as long as there is curtailed energy available, the battery is charging to store it. Otherwise, the battery discharges to meet the energy demands of the ASHP only, offsetting any import from the grid. At the point at which the battery is depleted, the heat pump imports from the grid.

Figure 25 illustrates a curtailment event and the battery response. At 10.22 the setpoint of the Eday turbine is changed to ~250kW (marginally curtailed). At the same time, the battery starts charging at 3kW for the duration of the curtailment event. The SoC of the battery is increased from 6.2% to 8.8% as a result of storing the curtailed energy.

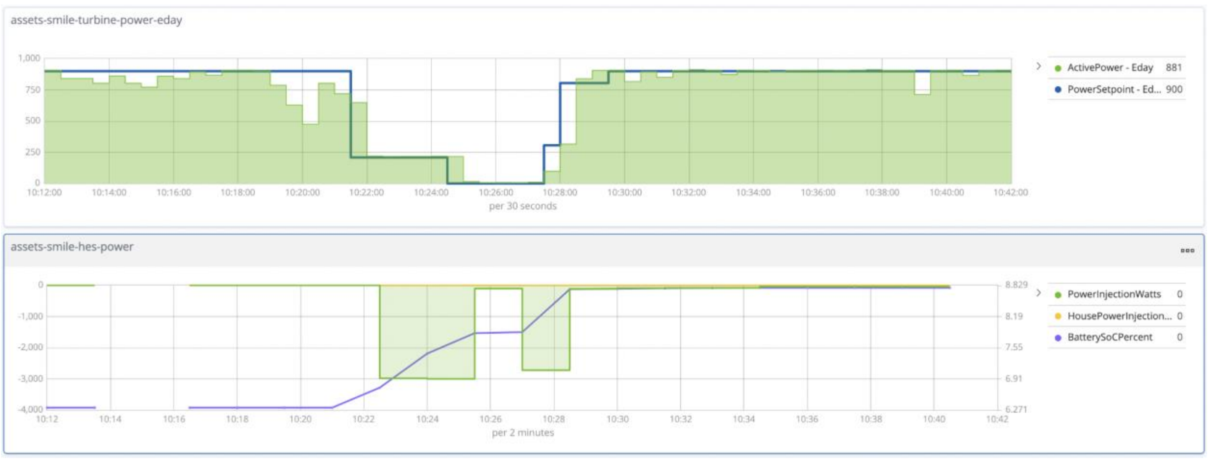


Figure 25: Lithium Balance battery charges in response to marginal curtailment at the Eday turbine

Figure 26 illustrates the battery discharging in response to the heat pump operation. After the curtailed event as described above, the battery is set to load match mode. At 15.00, the heat pump starts operating as scheduled by the local control system and the battery discharges to meet the demand of the heat pump in real time. From top to bottom, the sub figures illustrate: the state of charge of the battery and the discharge power; the on/off status of the heat pump; the power draw of the heat pump (measured by a separate power meter), and the flow and return temperatures of the water flowing through the central heating circuit.

Figure 26: Lithium Balance battery discharges stored energy from a previous curtailment event to match the power consumption of the heat pump

3.5.3 Curtailment Effectiveness

The Lithium Balance control system was delivered quickly and operated effectively throughout the project. Whenever a battery was available and in communication with the Kaluza platform, curtailment commands were respected and energy diverted to the battery as designed. Lithium batteries have been demonstrated to be a viable means of diverting curtailed energy consistently.

Given the reliability of the system in delivering during curtailment, good results were seen overall. During 2021, a total of **133 kWh** of energy was diverted by this system type during curtailment events. Had all five systems been continuously operational the maximum energy that could have been delivered was **296 kWh**, meaning that the systems delivered over 40% of the total possible energy savings possible.

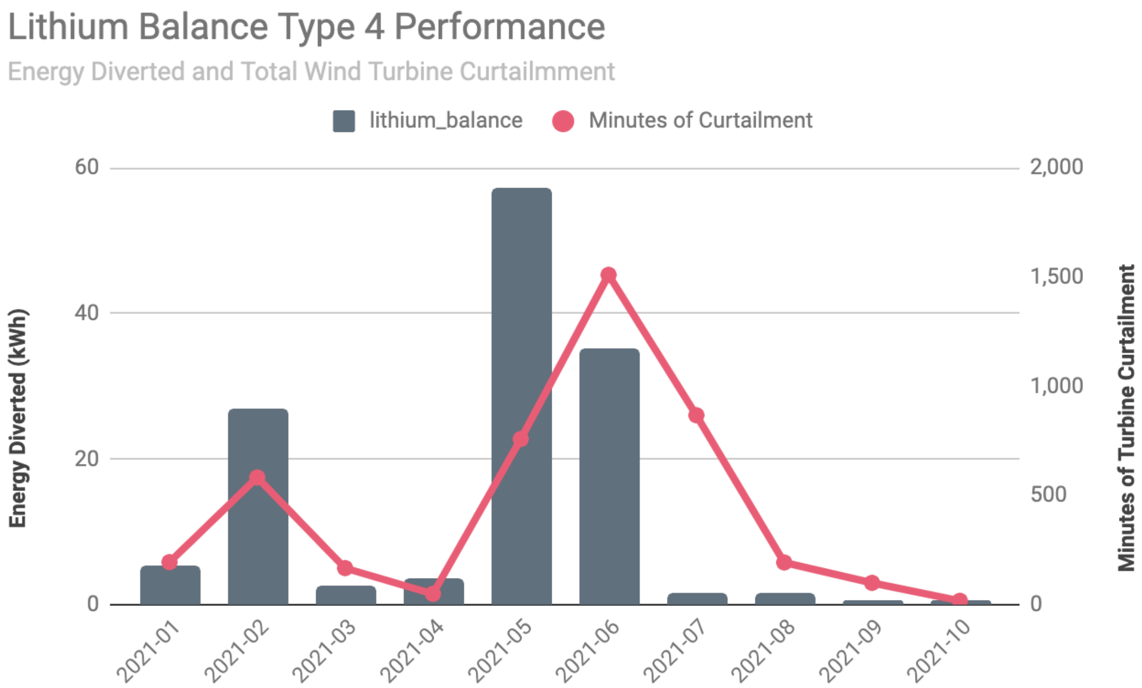


Figure 27: Curtailment and Type 4 Response

3.5.3.1 Issues Affecting Curtailment Effectiveness

A combination of communications issues and negotiations with the local DNO (SSEN) significantly reduced the amount of energy response that was delivered by type 4 systems overall.

Even though installation and commissioning of the battery systems proceeded smoothly, after a period of initially effective responsiveness, of the five systems installed, a maximum of three were able to communicate and respond at any given time as a result. In two of the five installations, the internet connection proved to be unreliable and not sufficient to keep the battery connected to the Lithium Balance back office. As a result, one battery was offline for too longer to ensure the health of the battery had not been compromised, resulting in sending the battery to Denmark for services, in place for an engineer making the journey to Orkney during COVID-19 lockdown. The second battery was not able to be stopped from dropping to critically low state of charger. This is resulted in a requirement of manual recharge of the battery to bring back to within the inverter's operating range. A software bug was highlighted as a result of this and implemented in all other BESSs to stop all other batteries possibly discharging to critically low state of charge.

The drop in response of two of the three previously functional battery systems after June 2021 was due to being forced to turn the batteries off during negotiations with the DNO. CES initially operated on a G98 connect and notify grid connection policy for the batteries. However, the DNO approached CES to challenge whether the applications could be approved retrospectively as singular installations, or whether close geographic proximity meant that they would need to be treated as multiple installations. CES were made aware by the local DNO, Scottish and Southern Energy Networks (SSEN) after installation and commissioning, that the grid connection for the batteries would not be a G98 Connect and Notify process as initially understood. Under the Energy Networks Association (ENA) Guidance for G98, SSEN designated the battery installations as a G98 multiple installation, as opposed to five separate single installations. This was due to the installations being in a similar postcode proximity, despite being on separate feeder circuits on the 11kV network. Under a G98 multiple installation, the batteries could no longer be connected via a connect to notify process, and had to be turned off until being approved as a multiple installation, a process which was not resolved before the end of the project. A single battery remained turned on, due to being the minimum allowable connection. CES, Lithium Balance and RS. Merriman collaborated to demonstrate compliance under the DNO's recommended G100 connection, but discussions with the DNO were stunted resulting in the confirmation of grid connection compliance not being achieved prior to the end of the project. However, prior to this issue, the battery systems demonstrated very high levels of effectiveness in responding to curtailment signalling.

3.5.4 Learnings

Type 4 systems and Lithium Balance batteries were able to respond reliably and are clearly capable of the task required of them in the SMILE Orkney project.

Lithium Ion batteries are an established and versatile technology with clear flexibility benefits across multiple use cases, and their deployment is expected to increase in many sectors. It is expected that market adoption of the residential battery systems will accelerate in the near future. The main drivers are expected to be:

- decreasing li-ion battery prices;
- constantly improving performance of batteries (calendar and cycle lifetime);
- increasing energy prices;
- favourable energy tariffs (variable price of electricity);
- decreasing feed-in tariffs;
- limiting the hosting capacity for PV in low voltage grids (expected DNO/DSO to curtail the feed-in power in the future);
- more favourable policies allowing new revenue streams (e.g. allowing aggregated battery response for participation in the ancillary energy markets);

A relevant learning through the installation and operation of the battery systems, is the importance of reliable data connection for monitoring of battery health. Due to local factors in two properties, unreliable/unaccessible internet connections resulted in concerns for two systems.

3.6 Type EV – Indra

3.6.1 System Configuration

Figure 28 and Figure 29 illustrate the configuration installed for B&B/tourist accommodation applications. The system consists of an Indra Smart+ EVSE (Electric Vehicle Supply Equipment) charger, directly integrated to the Kaluza platform - which allows an electric vehicle to charge at up to 7 kW power - and a web application that enables the end user to set charging preferences (e.g. ready by time, vehicle make/model, etc)

The Kaluza platform optimises the charge of the EV through the Indra charger to meet the user's primary need of being able to travel around the island. The charge is scheduled in such a way so as to maximise the opportunity for the charge to be powered by otherwise-curtailed energy from the wind turbines.

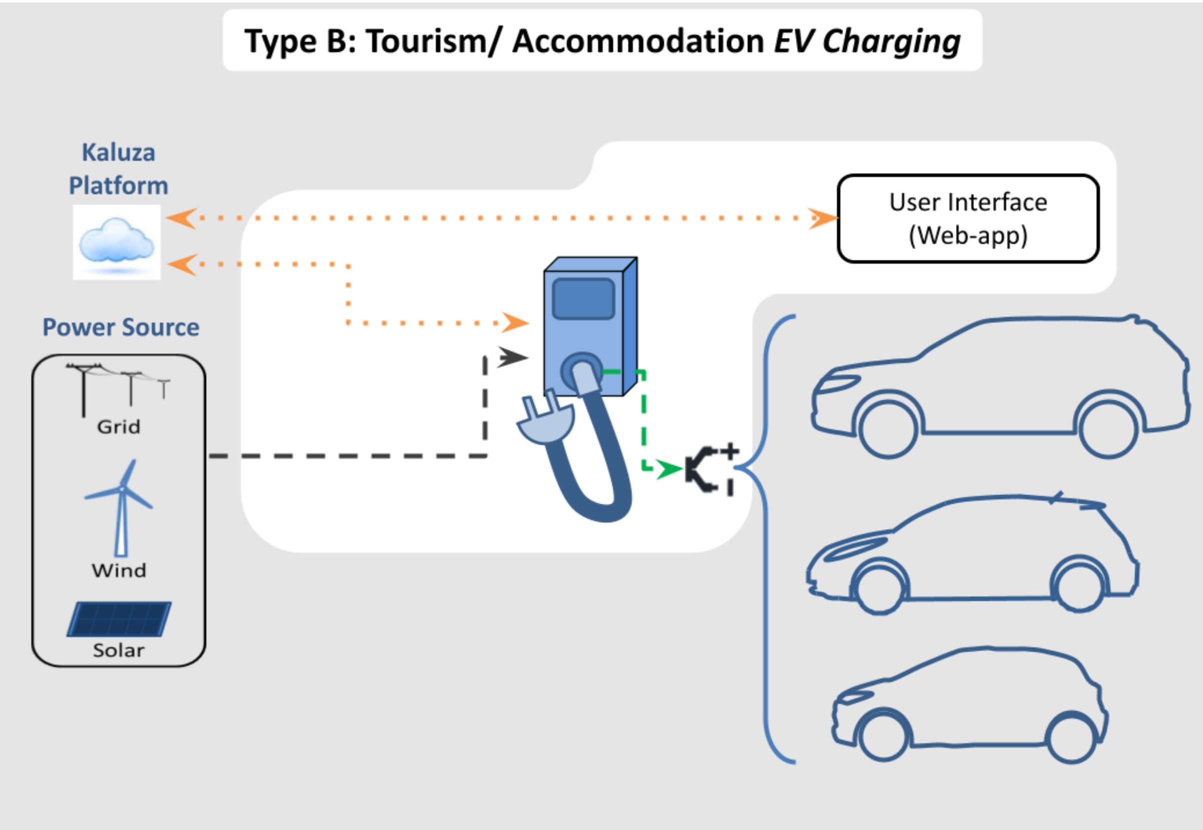


Figure 28: Indra/Kaluza platform B&B/Tourist accommodation EV charging system configuration

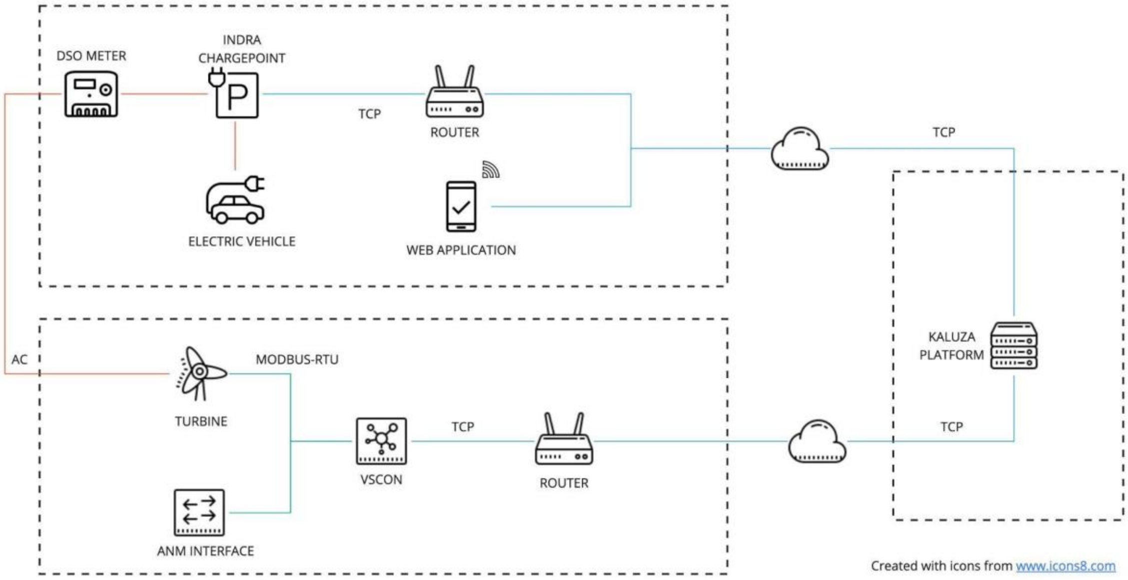


Figure 29: Indra/Kaluza B&B/Tourist accommodation EV charging integration configuration

Table 9: Key components and their purpose in the B&B/tourist accommodation system configuration

Component	Description/Specification	Connectivity	Location
VSCON	The VSCON unit monitors for, and transmits curtailment information from the wind turbine and the local smart grid (ANM interface).	Modbus-RTU/TCP from the wind turbine and ANM interface. Ethernet (TCP) to onsite router.	Wind Turbine
Kaluza Platform	Cloud-base control aggregator responsible for the smart functionality controlling of all equipment (either directly or indirectly), on both the generation and demand side of the SMILE infrastructure.	TCP connection over the public internet between internet routers located at wind farms and customer's homes.	Kaluza Data Centre
Customer App	The app will be installable and operable on a smartphone or tablet that will allow property owners to inform the Kaluza platform the quantity of charging	Operate via participant's wi-fi or mobile comms network, and transmit the data to the Kaluza Data Centre for processing	Business/ Tourism Site premises

	required and by when		
Indra Smart+ Charger	7kW charger with a proprietary communications protocol to the Kaluza platform. The charger will be a universal untethered charger in order to accommodate any EV.	Power connection to the properties distribution board, with a comms link via either a LAN or wifi connection to the properties router.	Principally businesses/ tourism site premises, with potential for some domestic properties.

The specific Type 4 configurations installed during the project are listed in Table 10.

Table 10: Quantity and type of Indra EV charging systems installed

Configuration	Number of properties installed
Indra EVSE B&B/tourist accommodation EV charging systems	22

3.6.2 Curtailment Operation

The chargers were installed at two types of properties:

- Bed and breakfasts ("BnBs") - for the BnB owners, or customers staying at the BnB, to charge their electric vehicles; and
- Residential properties - for residents and visitors to charge their electric vehicles.

We shall refer to the BnB owners or residents who authorised the installation of the chargers as "owners", and all sets of end users of the chargers (which can include the BnB owners, visitors to the BnB as well as residents at the residential properties) as "users" for the rest of this section.

Once the Smart+ is installed at the property, owners are invited to sign up to the companion web application associated with the charger. When the owner completes the sign up for the companion app, it enables Kaluza platform to take on intelligent control of their associated Smart+.

For the SMILE Orkney project, there are a few factors that influence the charging path determined by Kaluza platform's algorithms for the Smart+, which are:

- Plug in state of a vehicle into the charger
- The remaining energy requirement
- The user's "ready by time"
- The owner's energy tariff
- The occurrence of a curtailment event

If a vehicle is not plugged in, it follows trivially that no curtailment mitigation can be delivered by the platform.

For the purposes of the project, the remaining energy requirement for all vehicles associated with the installed chargers was determined to be 25 kWh. This essentially means that the algorithm will guarantee that the car battery is either at 100% state of charge, or that at least 25 kWh of energy is delivered to the vehicle by the user's indicated "ready by time" regardless of the occurrence of curtailment events. This is important as it gives the user sufficient battery capacity to explore the island regardless of the occurrence of curtailment on a particular day.

The "ready by time" is the time by which the user can indicate when they need the energy requirement fulfilled. It can be set by the user for every day of the week using the companion web app, as shown in Figure 30 below. Typically, for a vehicle that plugs into the charger in the evening, the user is expected to enter a ready by time that is in the early hours of the morning, for example 7AM. This gives Kaluza's algorithms the necessary flexibility on when to charge the car so as to mitigate curtailment. If the user indicates a "ready by time" that is soon after the vehicle has plugged in, the algorithm will prioritise delivering as much of the energy requirement as possible by the "ready by time", leaving little room for curtailment mitigation.

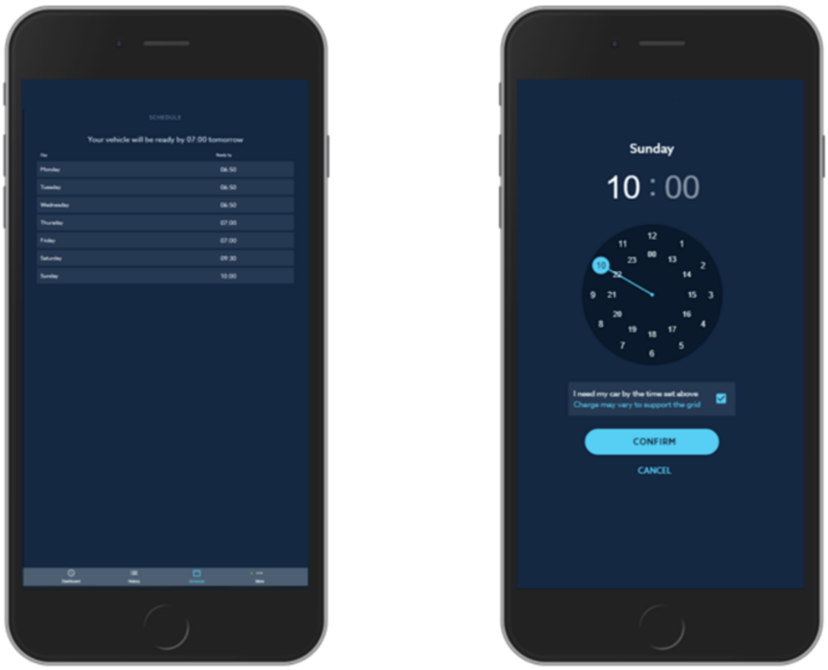


Figure 30: Setting the "ready by time" for the charger

The owner's energy "time of use" tariff can be set through the companion app as shown in Figure 31 below, allowing the owner to specify the different hours of the day during which they are exposed to different energy unit rates. For hours of the day where the energy unit rate is the cheapest (known as the "off-peak" period), Kaluza platform's algorithms schedule charging of the car in such a way that up to 25 kWh just in time by the "ready by time", provided there were no additional curtailment events. The charger and therefore the algorithm is unable to infer accurately the car battery's state of charge while it is plugged in, so if the car battery got to 100% state of charge earlier than the full delivery of 25 kWh, then it would be ready earlier than the "ready by time". This type of "just in time" charging guarantees that the user has enough capacity in their car battery to drive around the island during the rest of the day. If the owner is on a single-rate tariff, that is they are exposed to the same energy unit rate during all hours of the day, the charger could be used for curtailment mitigation at any point of the day until the “just in time” charging kicks in to meet their ready by time.

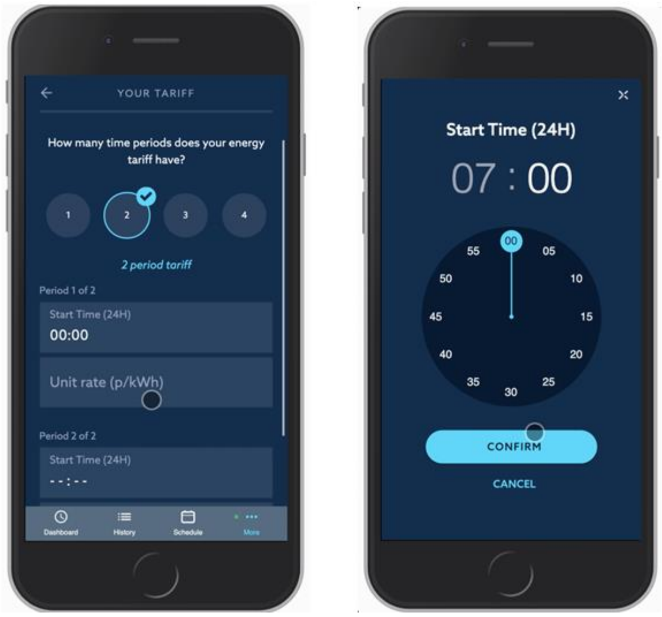


Figure 31: Setting the owner’s energy tariff

Finally, and perhaps most importantly, if there were curtailment events occurring anytime during either, the off-peak period or up to four hours prior to the start of the off-peak period, Kaluza’s algorithm would deliver request charging at 7 kW until the event ended to mitigate as much curtailment as possible. The reason for allowing four additional hours prior to the start of the off-peak period as a window for curtailment mitigation was because it was deemed that the typical overnight off-peak period alone did not sufficiently overlap with the hours of the day during which wind curtailment was likely to occur, and therefore expanding the window allowed for more overlap.

The algorithm also keeps track of how much energy is delivered during the entire plugin period. This means that once such curtailment events occur, the algorithm determines that there is an overall lower energy requirement than the initial 25 kWh. This means that the aforementioned “just in time” process described above can kick in later than during a day when there were no such curtailment events upon which the algorithm acted, leaving more room during the off-peak period for the algorithm to respond to more curtailment events.

One undesirable side effect of charging the car during a curtailment event is that - due to the hardware configuration of the Smart+ - once the charger has started delivering charge during such an event, it needs to at least be “slow charging” at 1.4 kW until any of the below happens:

- the car is at 100% state of charge - at which point there is no capacity left for curtailment mitigation
- the car is unplugged from the charger - at which point there is no possibility for curtailment mitigation.
- The next curtailment event - at which point the algorithm will start charging again at 7 kW and go back to 1.4 kW once that curtailment event has ended

● The algorithm starts charging at 7 kW to meet the remaining energy requirement "just in time" as described above

There are other factors such as - how quickly the car battery can charge at a particular point in time as determined by the battery management system - that can affect the outcomes of the charging path calculation and total amount of energy delivered by the "ready by time". However for the purposes of simplifying the illustration of how the algorithm works, such details have been excluded.

To demonstrate how this all comes together, consider a charger with the following settings:

- An off-peak energy tariff period between 00:30-07:30
- A peak energy tariff period between 07:30-00:30
- Ready by time of 06:30
- An exact energy requirement of 25 kWh such that the car is at 100% state of charge after 25 kWh has been delivered

During a day without any curtailment events, Figure 32 shows what the charging pattern would look like. The algorithm determines that charging should start at 02:30 so as to deliver 25 kWh "just in time" for the 06:30 ready by time user requirement, delivering up to 3.5 kWh of energy every half hour (i.e. charging at 7 kW to deliver the requirement).

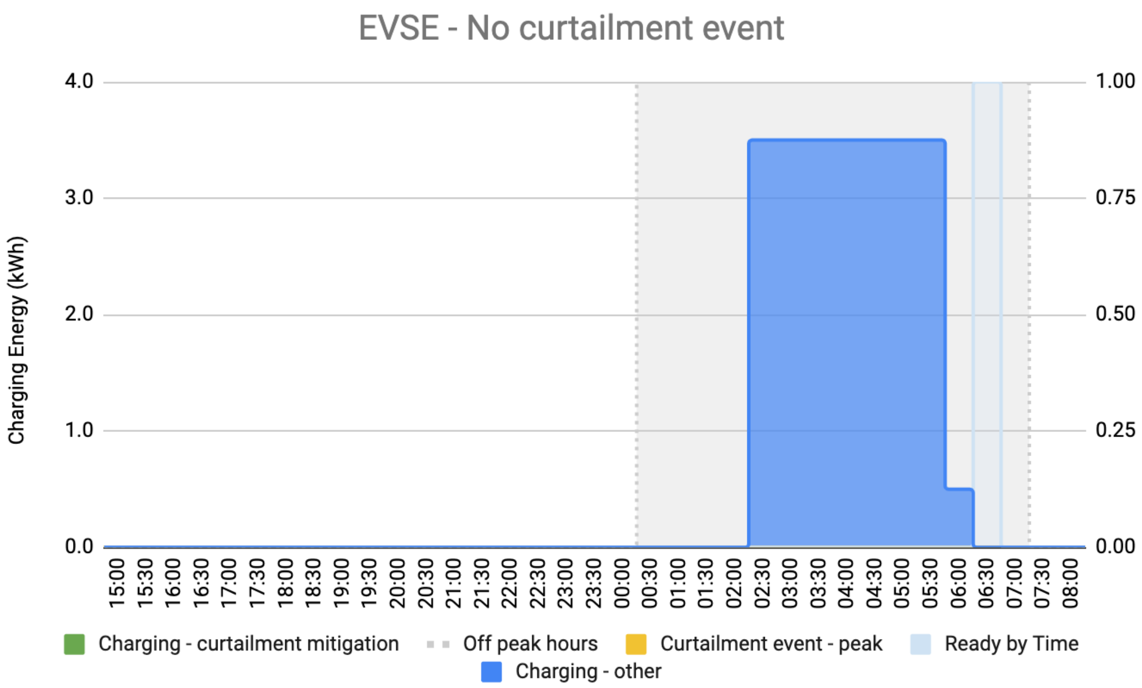


Figure 32: EVSE Charging, no curtailment events

Figure 33 shows a day with curtailment events happening during the early hours of off-peak period. The first curtailment event starts at 01:00 and lasts for 30 minutes, and the algorithm requests delivery of 3.5 kWh of energy (at 7 kW power) during the event. From 01:30 onwards, "slow charging" occurs at 1.4 kW which is the minimum charging power as required by the hardware configuration once charging has started, and a total of 2.1 kWh of energy is delivered from 01:30 to 03:00. The second curtailment event then starts at 03:00 and again lasts for 30 minutes, and once again the algorithm requests delivery of 3.5 kWh of energy. After that, “slow charging” starts again but only lasts for 30 minutes as by then the algorithm starts requesting 7 kW charging or up to 3.5 kWh of charging until the “ready by time” of 06:30 AM to ensure that a full 25 kWh has been delivered by then.

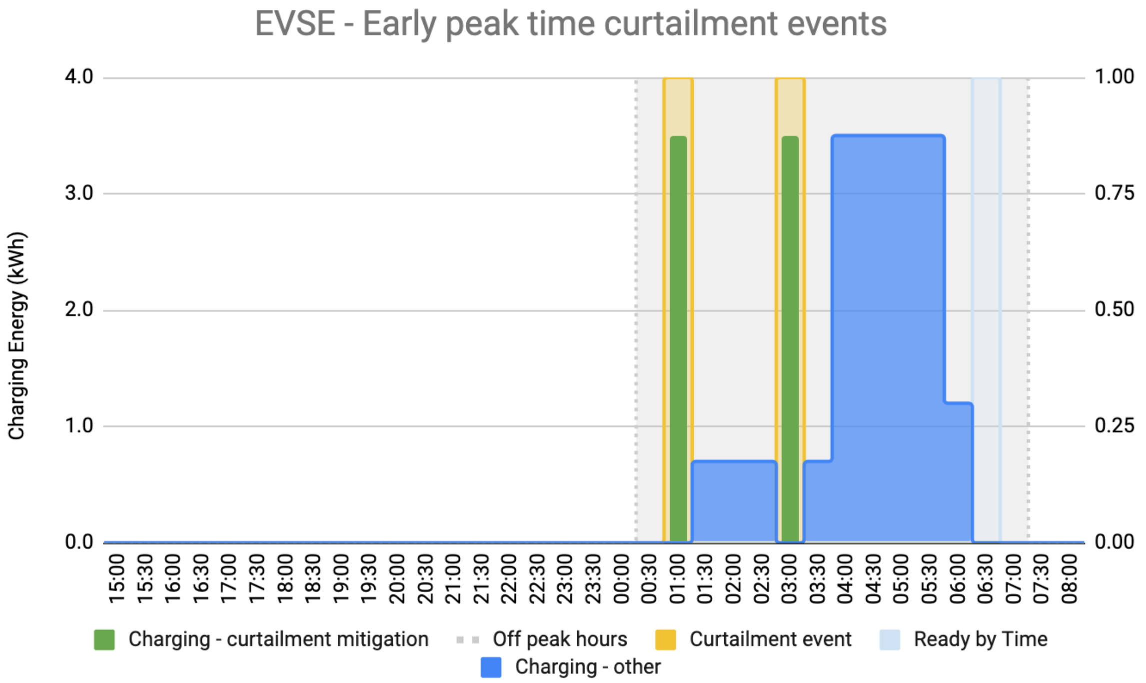


Figure 33: EVSE Charging, curtailment events during early peak hours

Figure 34 a day with curtailment events happening both during the peak period and the off-peak period. The first curtailment event starts at 17:30 and lasts for 30 minutes, however since this is more than 4 hours away from the start of the off-peak period, the algorithm does not request charging and therefore no curtailment mitigation occurs. The second curtailment event starts at 21:00 and lasts for 30 minutes. This event is within 4 hours from the start of the off-peak period, and so the algorithm does request charging and 3.5 kWh of charging is delivered during this period. From 21:30 until 02:30, “slow charging” occurs and a total of 7 kWh is delivered during this period. At 02:30, the third and final curtailment event starts and lasts for 30 minutes, and once again the algorithm requests a delivery of 3.5 kWh. From 03:00, slow charging occurs until 05:00 when the algorithm starts requesting 7 kW charging until the car is full by the 06:30 AM “ready by time”.

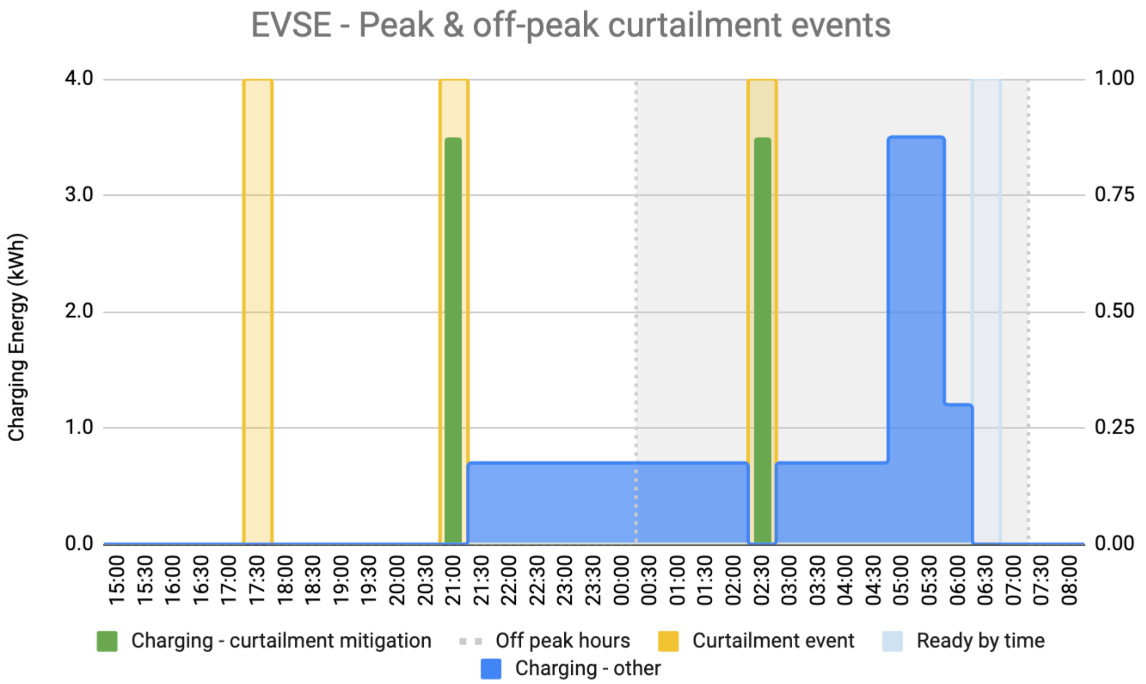


Figure 34: EVSE Charging, curtailment events peak & off-peak hours

Figure 35 shows a real-world curtailment event in action, with the current consumption as observed from the charger stepping up during a marginal curtailment event at the Eday turbine (setpoint falling below 900 kW), and current consumption stepping back down when the turbine is uncurtailed. This particular charger is on a single-rate tariff which means that the charger could respond to a curtailment event at any point during the day.

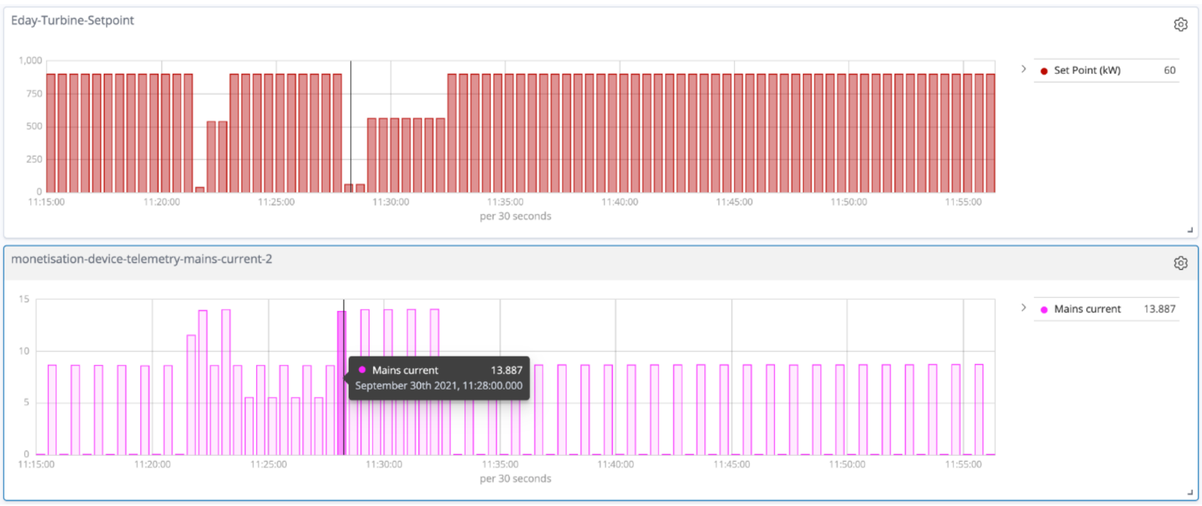


Figure 35: Indra EVSE charges at higher power in response to curtailment event

3.6.3 Curtailment Effectiveness

A control system was successfully implemented for Indra EVSEs on Orkney, and demonstrated to be capable of diverting energy during curtailment periods. Several charge points were seen to respond correctly during the trial, with a limited but material energy response provided.

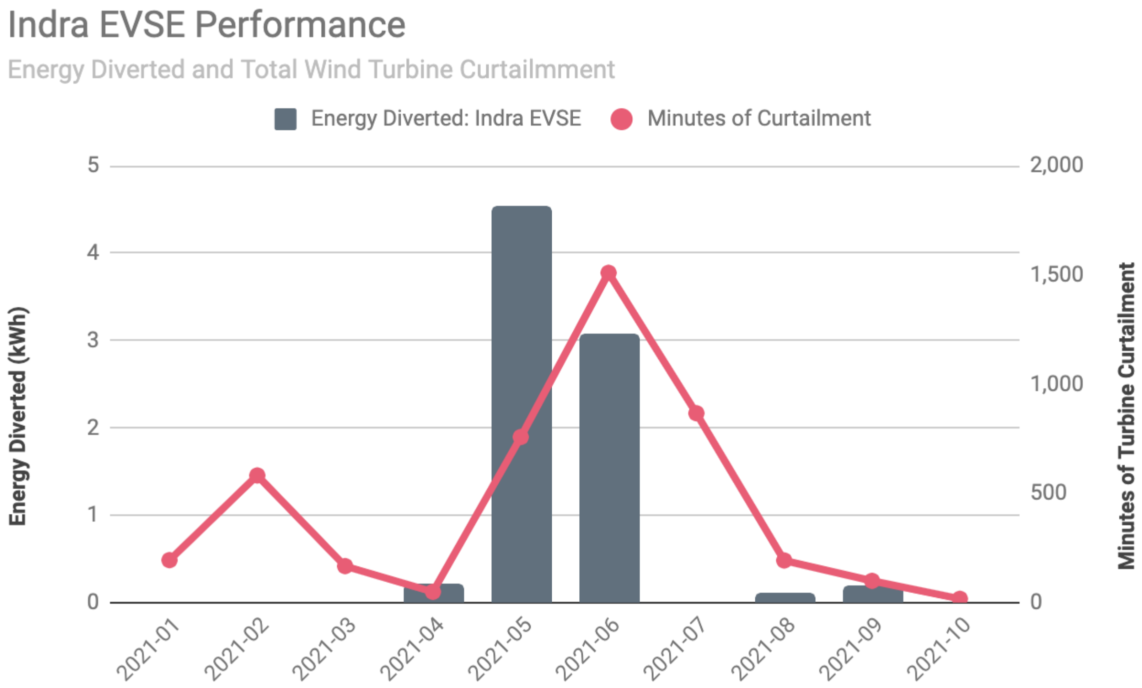


Figure 36: Curtailment and Indra EVSE Response

There was a lot of diversity in property types and participant usage of EVSE units in the Orkney trial, and a lot of complexity involved in creating a bespoke version of an existing user control application for project participants to use. Since the end users that utilised these charge points were primarily self-catering guests, it is possible that they either did not own an electric vehicle. If they did have an electric vehicle, it is also possible they were not fully cognisant of the benefits of smart charging and therefore may have opted to boost - resulting in a full car and rendering the chargers unavailable for curtailment mitigation. Further, occupancy at many of these properties may have been low given the overall reduced travel to the islands during the Covid-19 pandemic. The result of these compounded difficulties was a relatively small number of successful events over the course of the project concentrated almost entirely in the months of May and June when the longest periods of wind turbine curtailment were observed (Figure 36).

As with other device types, analysis was also conducted to determine the maximum possible energy that could have been diverted during curtailment events had all systems been fully operational. This analysis looked at all cases when a vehicle was connected to a charge point. Over the same period of time, this figure was **1,735 kWh.**

It is worth noting that this latter figure is likely to be significantly inflated as it cannot account for the state of charge of connected devices, assuming instead that any device connected could respond to a curtailment event. The true value of the 'curtailment opportunity' for 2021 will therefore be considerably lower.

3.6.3.1 Issues Affecting Curtailment Effectiveness

Lack of end user need
As mentioned previously, it is possible that several self-catering guest end users did not have an electric car and therefore no need for smart charging - meaning that fewer cycles were available for curtailment mitigation. This would have been exacerbated by reduced travel to the islands during the COVID-19 pandemic induced lockdowns.

Vehicle Compatibility
Through the real world testing in Orkney, it was found that one EV charger which was solely dedicated to charging a Citroen C-zero, found it very difficult to charge the vehicle in the fashion required by the project. A compatibility issue meant the charger was unable to "wake up" the vehicle when it was time to charge. After this was highlighted, OVO Energy charged the manner in which the charger operated in order to navigate this. The altered method was to charge the vehicle straight away at a minimum rate of charge (~1.4kW), and then turn charge at full power during a marginal curtailment event. This avoided the inability to wake up the vehicle when required, and provided the user with a reliable charger.

Poor connectivity and 'home alone' mode
Control of EVSE systems is complex and requires consideration of not just how the chargepoint will behave but also the vehicle itself. When communications are inconsistent due to connectivity issues, vehicles can revert to default behaviour and charge immediately on connection, rather than delaying until called upon. This is known as 'home alone' mode, and inhibits response to events. There is evidence that a large number of installed units were in home alone mode for much of the trial.

'Boosting' behaviour
Smart chargers are required to allow the user to override smart behaviour at any time by using a feature known as 'boost'. This can be triggered by hardware or software, and causes the device to charge immediately, making response to events impossible. OVO Energy have conducted extensive research on boosting behaviour through propositions enabled by the Kaluza platform, and have generally found that once a pattern of boosting behaviour is established it is unlikely a user will revert to smart charging. It has also been found that boosting behaviour is usually triggered by a lack of understanding of how smart charging works, or a lack of confidence in a vehicle being ready when needed - this is particularly exacerbated by the fact that the end users were primarily self-catering guests, meaning they are not as aware or invested in the need for smart charging of the device. The bespoke nature of the interfaces, control and user journeys associated with the experience for SMILE participants was likely to have been a contributor to the prevalence of boosting behaviour.

3.6.4 Learnings

The outcomes of smart electric vehicle charging are determined to a great extent by user behaviour and rely heavily on faith in the underlying technology, which is only likely where user experience is carefully curated and highly stable. While the actual dispatch of devices when required to mitigate curtailment was proven and worked consistently for some systems, a key learning from this element of the project has been that more emphasis needs to be placed on consistent user experience. It is recommended that future similar initiatives are designed around established platforms which are able to simplify and manage experience without extensive customisation. Customisation which deviates even very slightly from carefully curated onboarding journeys, designed to maximise smart charging, is likely to have unpredictable effects on usage and deliver inferior results to those realised by the standard product offering.

As has been noted above, the availability of vehicles requiring charging must be factored into expectations of the delivery of flexibility, and future projects are advised to seek a detailed understanding of usage patterns for participants before decisions are made regarding installation of hardware.

Finally, the SMILE project deployed smart chargers to a number of self catering accommodations. In retrospect, the lack of predictability of behaviour of such sites may make them sub-optimal candidates until electric vehicle usage is more widespread. It may also be possible that end users (self-catering guests) that utilised these charge points either did not own an electric vehicle and if they did, were not fully cognisant of the benefits of smart charging and therefore may have opted to boost. Further, occupancy at many of these properties may have been low given the overall reduced travel to the islands during the Covid-19 pandemic.

3.7 Type EV - Trakm8

3.7.1 System Configuration

The system integration configuration for the Trakm8 EV charging solution is illustrated in Figure 37 and Figure 38. In this configuration, OCPP (open charge point protocol) charge points are connected to the Trakm8 back-office system, where, with the use of telematics directly from the EVs, Trakm8 determine the optimum time to charge the EV, based on factors such as predicted use pattern and EV state of charge.

A simple API was provided by Trakm8 to OVO that enables the Kaluza platform to query at any point the amount of dispatchable load available to the Trakm8 system, based on the number of vehicles connected to the Trakm8 back office. In the event of curtailment, this enables the platform to dispatch a corresponding amount of load, with an appropriate API call.

A description of each system component is provided in Table 11.

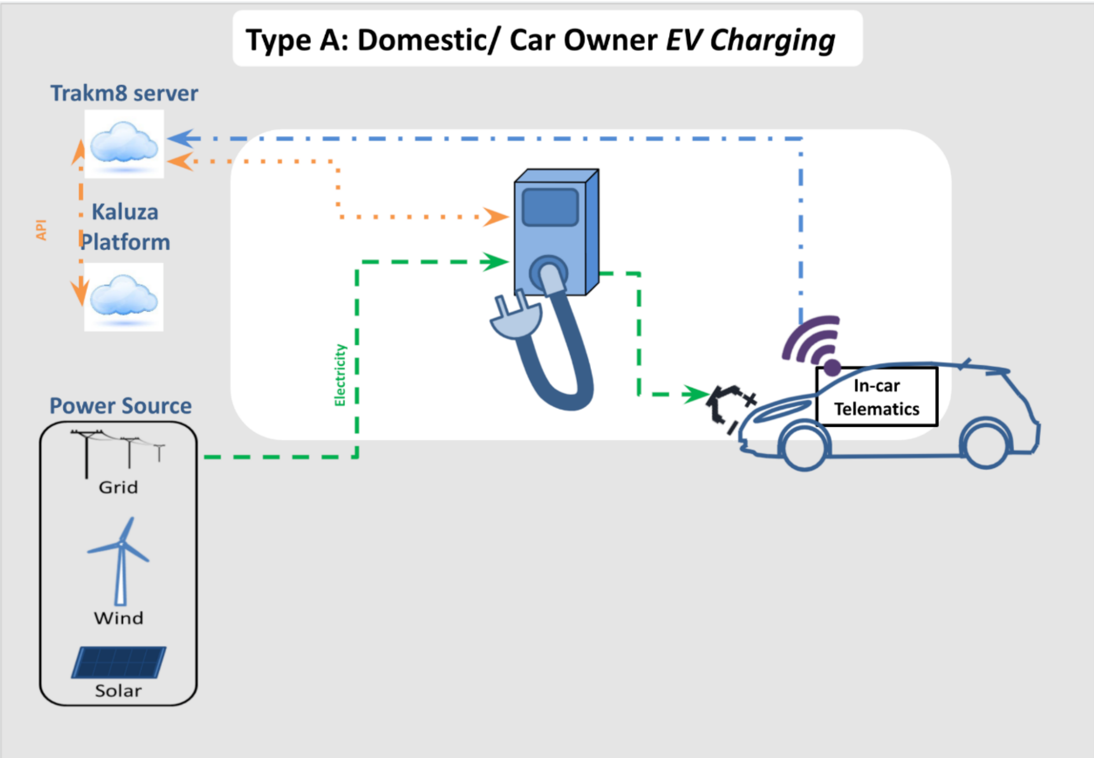


Figure 37: Trakm8/Kaluza EV charging system configuration

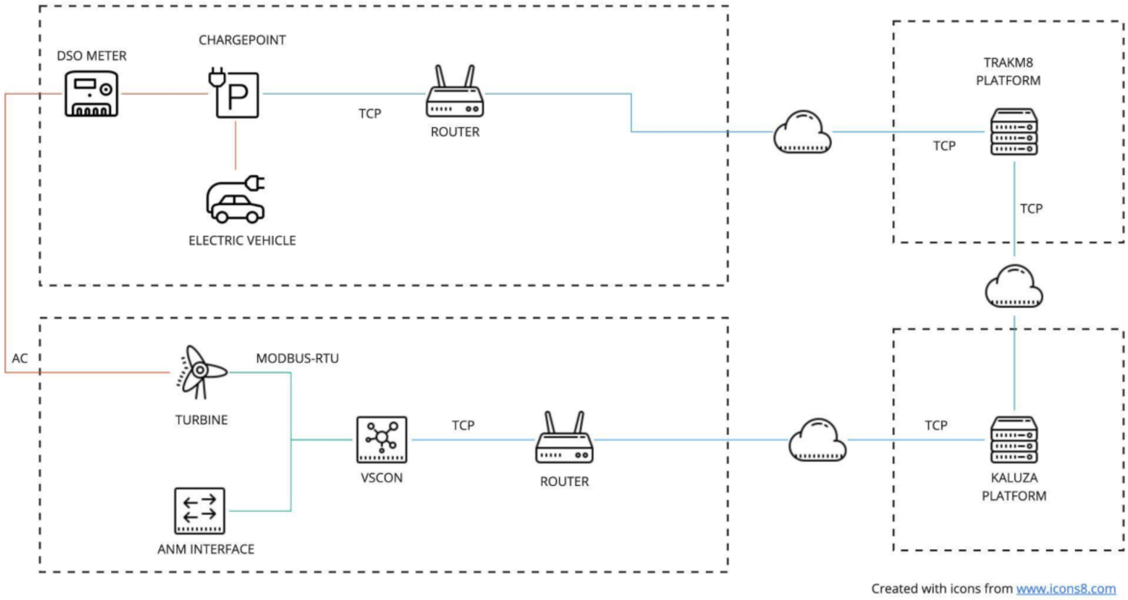


Figure 38: Trakm8/Kaluza platform EV charging integration configuration

Table 11: Key components and their purpose in the Trakm8/Kaluza system configuration

Component	Description/Specification	Connectivity	Location
VSCON	The VSCON unit monitors for, and transmits curtailment information from the wind turbine and the local smart grid (ANM interface).	Modbus-RTU/TCP from the wind turbine and ANM interface. Ethernet (TCP) to onsite router.	Wind Turbine
Trakm8 Platform	To provide remote control of charging events and charge schedule prediction for connected OCPP chargers	TCP internet link between the Trakm8 platform and the customer's home's internet router	Trakm8 Data Centre
Kaluza Platform	Cloud-base control aggregator responsible for the smart functionality controlling of all equipment (either directly or indirectly), on both the generation and demand side of the SMILE infrastructure.	TCP connection over the public internet between internet routers located at wind farm and customer's home.	Kaluza Data Centre
OCPP 1.6 Charger	7kW Electric Vehicle charger enabled with	3G/GSM, or connection to	Trakm8 Data Centre

	OCPP 1.6 protocols; allowing for the remote controlling of charger output	properties internet router, allowing comms link to Route Monkey/Trakm8 Data Centre.	
Trakm8 Telematics	Trakm8 T10 Micro in-car telematics unit is a self-installed box that is plugged into the vehicle's OBD2 port. The unit transmits data via GSM back to the Trakm8 Data Centre	Physical connection with car. Wireless GSM comms connection with data centre.	EV's ODB 2 Port

Table 12: Quantity and type of OCPP1.6 compliant EV charging systems installed

Configuration	Number of properties installed
Trakm8 domestic owner EV charging systems	6

3.7.2 Curtailment Operation

In this configuration, Trakm8 (Route Monkey) reports to Kaluza platform in real-time the maximum aggregate energy that the connected fleet can deliver for the next five minutes, as well as the maximum power at which that can be delivered. If a curtailment event occurs during a period where Trakm8 reports available capacity, then the platform will request a dispatch of the total available capacity from Trakm8. Trakm8 can then use this information to decide how to deliver the charge within the fleet.

The overall algorithm is captured in Figure 39.

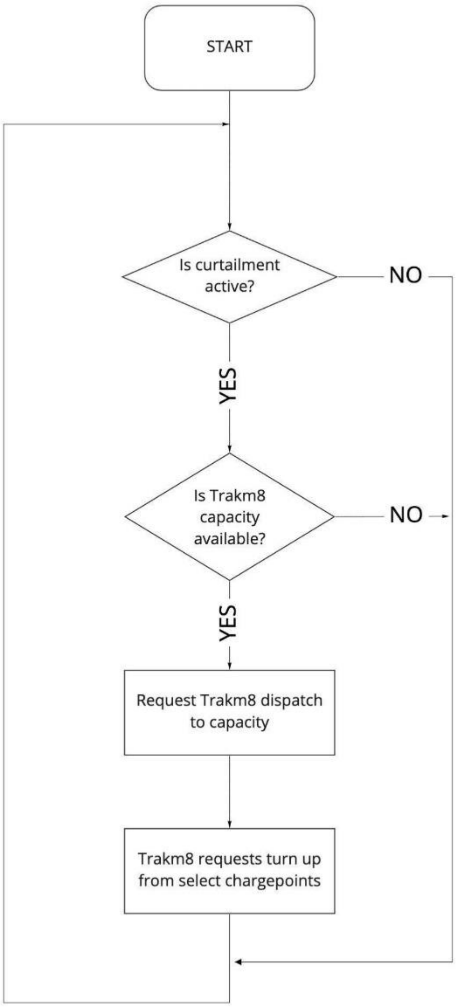


Figure 39: Type EVSE - Trakm8 control algorithm flowchart

Trakm8 uses an activity model based (ABM) approach. The algorithm runs multiple simulations to cover the future prediction horizon of interest, and then captures these in a probabilistic demand profile. This profile provides confidence levels around the potential demand in future time slots, and therefore used by Demand Response (DR) or similar services to estimate the capacity available from EV charging in the short or longer term.

Figure 40 illustrates what this looks like in practice. The top chart shows curtailment events in both blue and green. The middle chart shows in red, the maximum available capacity for turn up and in green the actual capacity turned up as reported by Trakm8. The bottom chart shows the commands requested for dispatch from Kaluza platform to Trakm8. By observing the highlighted line that cuts across all the 3 charts, you can see that as soon as there is an overlap between the curtailment event in the top chart and available capacity in the middle chart, the platform requests a dispatch event 7.5 kW turn up. With the other two curtailment events, there is no overlap of the curtailment event with available capacity from Trakm8 and therefore the platform does not request a dispatch event turn up.

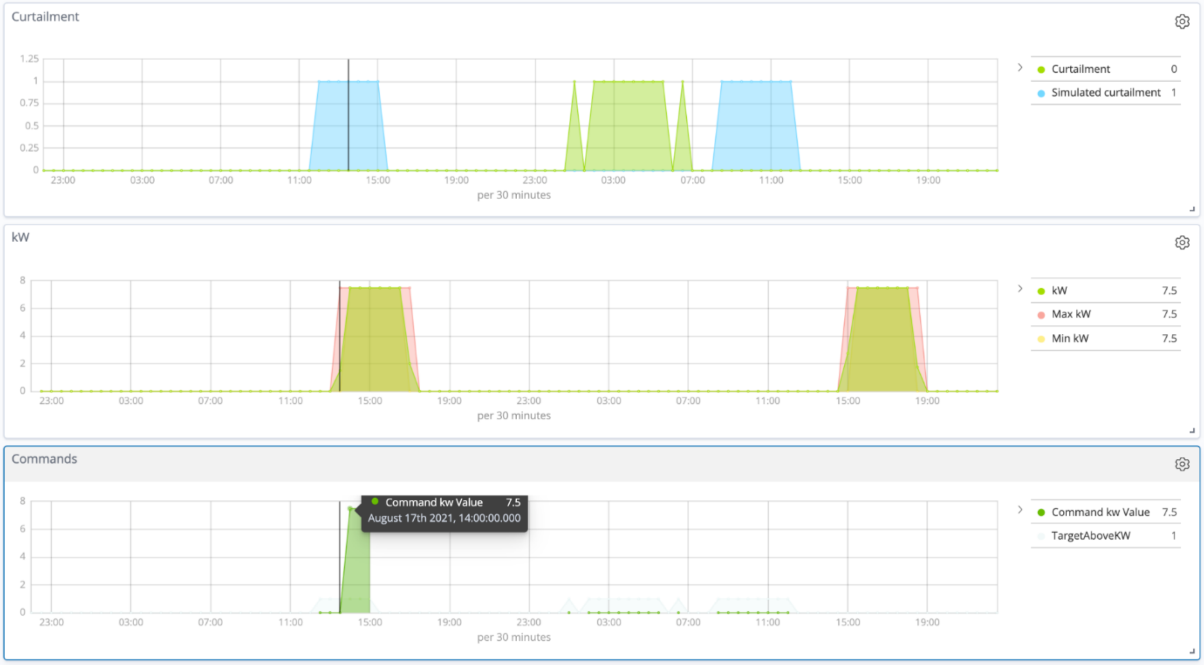


Figure 40: Kaluza requests dispatch from Trakm8 system when curtailment and available capacity overlap

3.7.3 Curtailment Effectiveness

There is some evidence from data provided to OVO Energy that the Trakm8 control algorithm was operating as expected when brought online in September 2021. Kaluza platform was able to process data from the Trakm8 API, and there were examples of charging sessions exhibiting the expected behaviour. One case is shown below, in which a vehicle was plugged in around 13:00 and immediately charged partially to 80% SoC. Overnight, the vehicle remained in this state and a top-up charge was applied at 04:30 to ensure the vehicle was ready for use in the morning. The 'Max kW' value indicates that there was capacity to absorb curtailed energy between the two charge periods.

Unfortunately, efforts to make a plugged-in vehicle respond to either real or simulated curtailment events during such periods of readiness were not successful, and there were no instances of a Trakm8 vehicle responding to a command to divert curtailed energy during the data collection phase of the project.

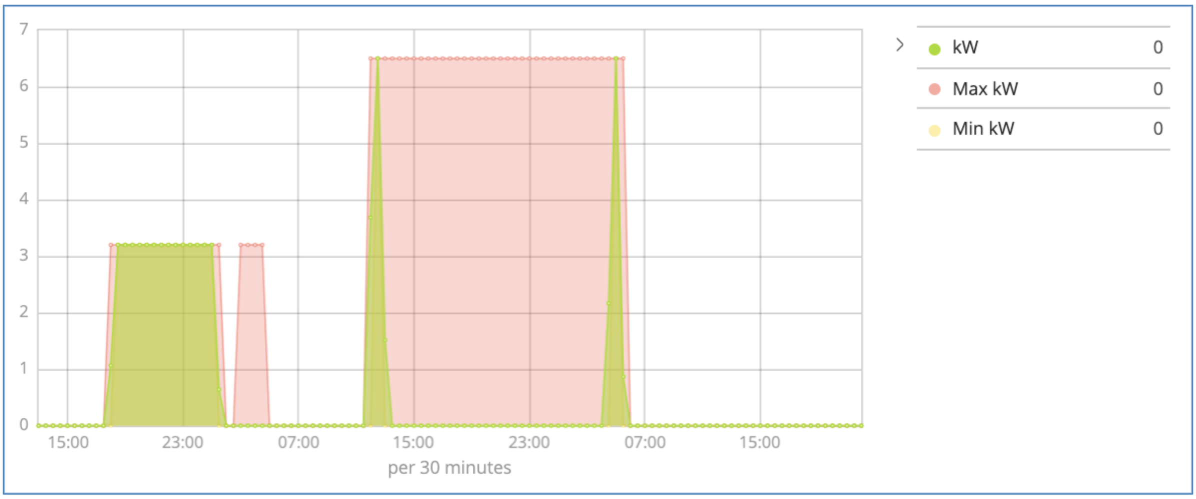


Figure 41: Trakm8 control algorithm testing

3.7.4 Learnings

In August 2021, Trakm8 successfully performed a live demonstration of asset control using a similar set of devices as those installed on Orkney. This indicated that the control algorithm concept applied could yield response in a controlled environment.

As with Indra devices, vehicle availability was unreliable and there were connection issues with several chargepoints. This meant that testing opportunities were severely limited, with only one chargepoint in operation by the end of October, and only a small handful of charge sessions having been attempted by the participant owner.

Upon deployment of the OCPP1.6 compliant EV chargers in Orkney, it was quickly identified that the chargers were losing connection to Trakm8's backoffice. This would occur when the property's broadband internet connection was lost momentarily, which can happen in Orkney and other rural locations. The chargers would have to be manually reset by turning the unit off at the RCD and turning back on again. This would typically reconnect the charger until the next drop in the internet again. The only charger which remained consistently connected was the unit that was connected via 4G router, instead of the properties broadband router. Investigations between CES, Trakm8 and the manufacturer were unable to correct this fault. Trakm8 confirmed that they did not witness the same connection failure during desktop tests prior to Orkney deployment. This model of charger can be enabled with an internal 4G router. This is an additional cost at the point of procuring the chargers. This would have been a beneficial method of navigating flaws in broadband connections.

Deployment of the six chargers in Orkney were delayed significantly due to the time required to ensure that the chargers were OCPP 1.6 compliant and a cyber secure connection could be established.

The dispatch of a connected electric vehicle to absorb energy at appropriate times has been proven with the Indra systems, and we are confident that Trakm8 systems are capable of similar response with more testing and a larger number of devices available.

EVSE systems will play a significant role in load management and energy balancing in the future, and Kaluza's work throughout the UK seeks to demonstrate the versatility of electric vehicles in this role. On smaller islands such as Orkney, the use of these systems is somewhat restricted by the relatively low typical mileage requirements on the connected vehicles, as well as small fleet sizes. Clearly, the capacity for flexibility of an electric vehicle charger is determined as much by the usage of the connected vehicle as the duration of connection, and chargers of both types were not in sufficient demand during the project to offer significant response.

3.8 Type Aggregated Heat Load - HSO

3.8.1 Context

An industrial load was originally proposed to be the smart control switching of an existing electrolyser (operational November 2017), owned by EMEC (The European Marine Energy Centre) and located on the island of Eday at their tidal energy test site. The electrolyser was originally installed to provide storage and power and grid export management for tidal generation devices installed and tested at the site. Its system was then linked to the 900 kW local community wind turbine, 600 m away, using basic/manual switching, as part of the Surf 'n' Turf project funded by the Scottish government CARES Local Energy Challenge Fund. The aim under SMILE was to smarten the control and switching between the wind and tidal generators and the local grid, to maximise renewable generation and hydrogen production.

However, due to circumstances outside of the SMILE consortium's control and after close liaison and discussion with EMEC, a technical unavailability of the hydrogen electrolyser during the timescale of the SMILE project was confirmed; the proposal to include it within the SMILE project was therefore paused. The scope of the Orkney demonstrator was redesigned in 2019 to continue without hydrogen as part of the aggregated DSM loads.

As a replacement for industrial load, a proposal was accepted whereby the smart heat demand turn up asset from the Heat Smart Orkney project would be used to replace the industrial asset.

In the Heat Smart Orkney (HSO) project which commenced in 2018 and ended in 2019, 108 heating devices (hot water immersion heaters, and stand-alone intelligent electric Dimplex heaters) with a total potential capacity of over 200 kW were installed in participant households to create Demand Side Management (DSM) loads to mitigate curtailment at the community owned turbine on Rousay. The curtailment mitigation system in HSO was set up in a similar way to SMILE such that whenever there was a curtailment event at the Rousay turbine, the immersion heaters and Dimplex heaters would turn on, provided that they were not "at full capacity". The control was facilitated through a Kaluza platform connected and managed device called "Dynamo".

After the HSO project, these devices continued to be used for curtailment management of turbines in Orkney, as part of other demonstrators, through a third party marketplace platform whereby Kaluza platform could bid individual heating devices' flexibility into the marketplace so that they could be matched off against the curtailment management needs of multiple generator partners - starting with the Eday turbine. To enable the reintroduction of the HSO assets to the SMILE project, OVO continued supporting the device maintenance, bidding process and smart operation of the HSO assets through the third party marketplace as well as data capture to enable aggregated reporting of curtailment effectiveness of all asset types in SMILE. Over the course of 2021, OVO also facilitated the registration of the Rousay turbine with the third party marketplace so that curtailment events from Rousay could be acted on by the HSO assets.

3.8.1.1 The HSO Assets

Dimplex heaters consist of electric heating elements held between bricks, surrounded by insulation. As electric power flows through the device, the heating elements turn on and heat the bricks. A thermocouple held between the bricks and the insulation reads the brick temperature. Once the temperature reaches its heating limit (205 °C core sensor reading, equivalent to 700 °C brick temperature), the element is switched off. The insulation then enables the bricks to store heat until the room is desired to be heated, after which a fan and vent system enable the bricks to release the stored heat into the room. Both the immersion heaters and Dimplex heaters were installed with a Kaluza Dynamo 2-T controller which was used to control the switching on and off of the heating for curtailment mitigation. Additionally the dynamos had in-built metering chips which allowed the Kaluza platform to meter all electrical consumption through the devices along with the core temperature. Whilst the immersion heaters were linked to marginal curtailment and not the property's primary heating system, a "boost" override mode was enabled. This allowed households additional flexibility to immediately call for hot water during times with no marginal curtailment. The Dimplex heaters were also set up as supplementary, "secondary" heating in the homes - which meant that the customer's primary heating need would be met through a separate heating system even if there was no curtailment activity to heat the bricks. This meant that the heaters could be used primarily to mitigate curtailment if they were not at full capacity, and then the supplementary heat stored in the heaters could be used to reduce load on the primary heating system as well. Customers received a rebate on the cost of energy consumption associated with curtailment mitigation by the Heat Smart Orkney organisation.

3.8.2 System Configuration

A series of heater types were installed in participant households as part of the HSO project to create Demand Side Management (DSM) loads. These included: hot water immersion heaters, and stand-alone intelligent electric heaters. These were installed both in properties with and without pre-existing electrical heating systems. The average load of the immersion heaters and electric heaters, on a per device basis, was 2.3 kW.

A combination of direct and indirect, and vented or unvented Haetrae Sadia Megaflo hot water cylinders (ranging from 210 - 300 litres in size) were selected for installation.

A range of Dimplex Quantum electric heater models were selected for installation, including the following: QM50, QM70, QM100, QM125, QM150 (power ratings ranging 1.02 - 3.3 kW).

As mentioned previously, the Dynamo was used to control the switching on and off of heating for curtailment mitigation and all electrical consumption through the devices was metered using the Dynamo's in-built metering chips.

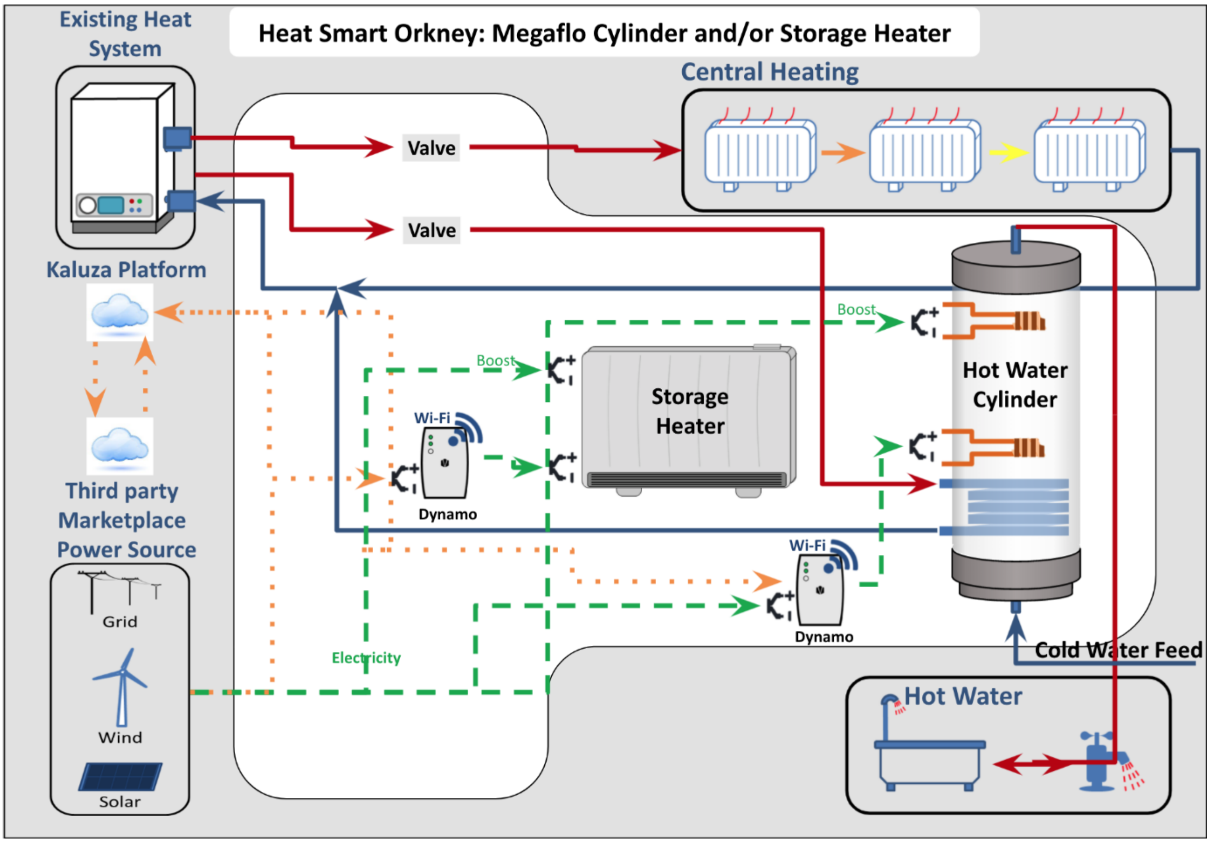


Figure 42: HSO Dynamo system configuration

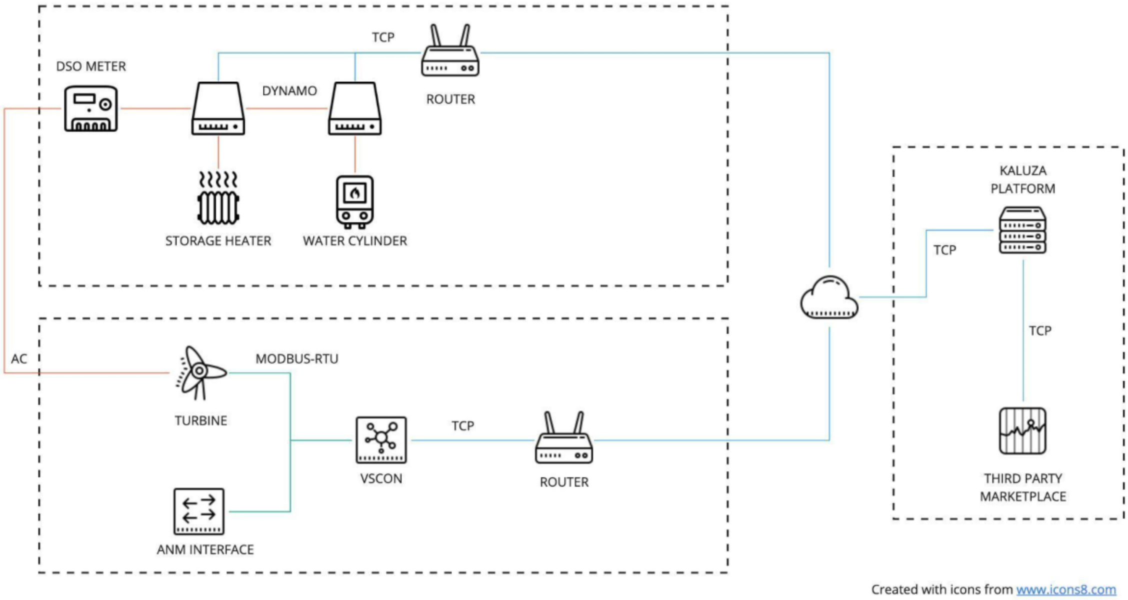


Figure 43: HSO Dynamo system integration configuration

3.8.3 Curtailment Operation

Within the context of the SMILE projects, the HSO assets were used to demonstrate a framework for a market driven approach for demand turn up, using a third party marketplace for curtailment mitigation. This meant that unlike the other installation types where Kaluza platform was directly responsible for the end to end from observing a curtailment event at the turbine to delivering curtailment mitigation - in this type Kaluza relied on a third party marketplace to which it sent bids for the assets which were matched off against offers from the turbines based on their curtailment need.

Regarding the use of the HSO assets in SMILE, Figure 44 illustrates how a curtailment event at the Rousay turbine resulted in the HSO aggregate asset turning up to the tune of 117 kW to mitigate curtailment. The result from the activity can also be observed through the rising brick temperatures for certain devices.

Figure 44: Dynamo-enabled storage heaters and immersion heaters turn up to mitigate curtailment at Rousay turbine

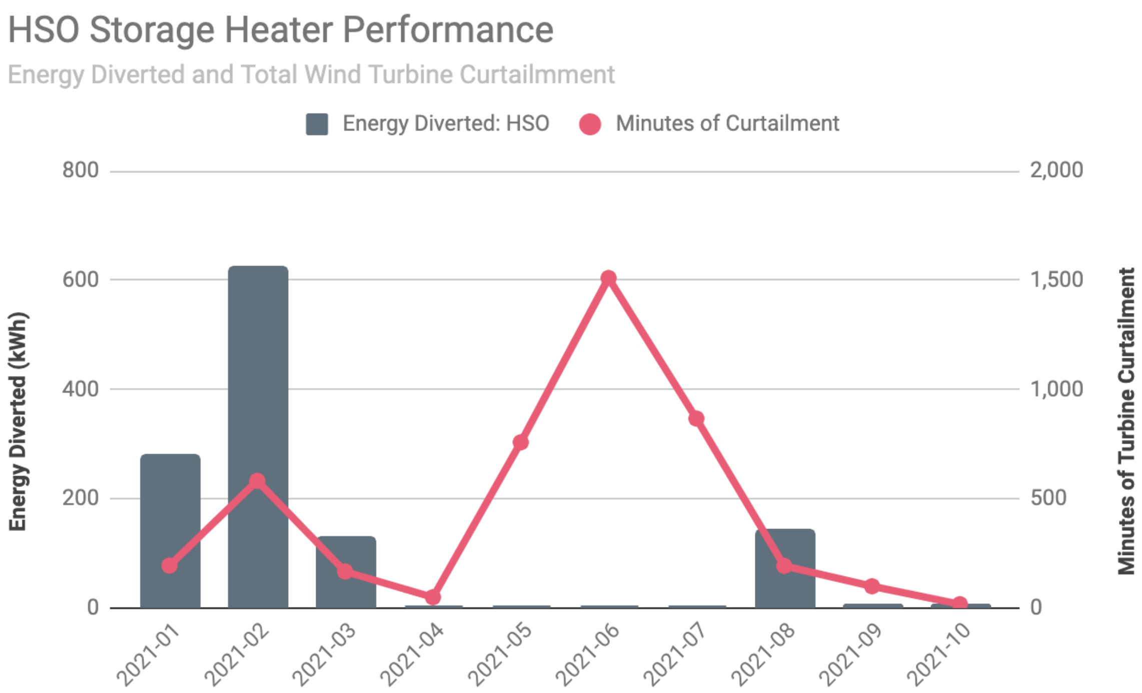
Initially, the system was set up such that the heating devices only responded to curtailment signals from the Eday turbine. However, towards the end of 2020 as mentioned before, the Eday turbine had a failure due to the two subsea power cables feeding Eday critically failed. The islands remained operating on a diesel generator set during this period. While this was the case, the community turbine was turned off, and there was no generation at the turbine until June 2021. This unfortunate event, combined with the decision to incorporate the HSO assets into SMILE in late 2020, led to Rousay turbine curtailment signals also being considered for response by the HSO assets.

Eventually, the Eday turbine came back online in May 2021 and the system capability was further improved so that it could respond to marginal curtailment at both Eday and Rousay turbines.

3.8.4 Curtailment Effectiveness

Since the activity of the devices was mostly driven by the need for curtailment mitigation, curtailment effectiveness was measured as the kWhs of consumption that occured at the same time as the turbines being marginally curtailed.

A control system was successfully implemented for HSO assets on Orkney, and demonstrated to be capable of diverting significant amounts of energy reliably during curtailment periods. Between January 2021 and October 2021, the HSO assets delivered **1,179 kWh** in curtailment mitigation, with nearly 623 kWh delivered in the month of February alone. This was despite the lack of operation of the Eday turbine from November 2020 to May 2021 and some issues faced with the third party marketplace integration during months of high curtailment activity.



Analysis was also conducted to determine the maximum possible energy that could have been diverted during curtailment events had all systems been fully operational and the majority of assets (based on maximum monthly connected devices) consistently connected to the platform. Over the same period of time, this figure was **13,107 kWh.** The HSO assets continue to demonstrate how effective storage heat can be when deployed at scale to manage grid issues such as curtailment.

3.8.4.1 Issues Affecting Curtailment Effectiveness

From November 2020 to May 2021, the Eday turbine was unavailable and curtailment mitigation was primarily driven by marginal curtailment activity at the Rousay turbine. In June 2021, the Eday turbine came back online and the system was reconfigured so that curtailment mitigation could be driven by marginal curtailment activity at both the Eday and Rousay turbines.

In April 2021, the third party marketplace operator - the integration with whom was in the critical path of the dispatch of the assets - had made a platform upgrade that was incompatible with the integration required with the Kaluza platform to operate the HSO assets. This resulted in the HSO assets not being called to mitigate curtailment from the months of April to July 2021. This unfortunately coincided with the months of May and June where marginal curtailment was relatively high. This issue was flagged up to the marketplace operator as soon as it was observed, but it was only fully resolved in August 2021.

Following the restoration of the marketplace to be compatible with HSO asset operation in July 2021, curtailment operation proceeded as expected - however marginal curtailment was generally low in the months from July to October 2021.

Furthermore, many devices were not online often enough - which meant that some of the capacity could not be utilised. The maximum number of devices that communicated in any given month between Jan 2021 to Oct 2021 was 76, and the median was 72. Additionally, analysis was conducted which suggested that connectivity issues were significantly more prevalent towards the end of the project. Some factors affecting the connectivity of the assets to the platform include:

- Customers deciding to switch off the dynamos / supplementary heaters themselves - this could be driven by either:
    - Change of seasons leading to reduced heat usage
    - Customers feeling like the incentive of free energy for supplementary heat was not sufficient
- Lack of reliable internet connectivity in the homes
- The firmware in the dynamo devices was unable to communicate with the platform - this was observed to be a repeating issue and where possible, OVO worked with Heat Smart Orkney (the organisation managing contact with the end customers) to send SD cards with updated firmware to bring the devices back online.

3.8.5 Learnings

SMILE demonstrates how effective a tool supplementary storage heat in customer homes can be to manage grid issues such as curtailment, when aggregated and deployed at scale. However, it is important to ensure that customers understand the benefits of such initiatives both for themselves (financially and in terms of supplementary heat) as well as the grid so that they keep the assets connected to the platform so they can be used effectively. In fact, it was so effective that hardware originally installed nearly four years ago with some ongoing firmware maintenance was sufficient to deliver a significant amount of curtailment response.

As with any highly dynamic system responding to real-time events, ensuring that there is reliable connectivity of the assets to the platform and up to date firmware on the hardware assets is very important. This would be exacerbated by internet dropouts in the area of the home where the assets are situated.

Introducing third party additional hardware to communicate with and control assets also introduces its own complexities - and it would be recommended to rely on the manufacturer's own systems, where possible. In fact, Dimplex's newest models already come with an option to get an in-home hub, which is connected to Dimplex's cloud IoT instance in the cloud - and so it would be recommended that in future projects a cloud to cloud integration with the manufacturer's own systems be pursued rather than introducing third party hardware.

Finally, the dependency on a third party marketplace meant that there were other factors that affected the performance of the system that were outside of the control of project partners. Even though issues were promptly looked at and investigated by OVO and the third party, since there were no strict Service Level Agreements on restoring service, quite a few opportunities for curtailment mitigation were missed from April to July 2021. This highlights the need to carefully consider the implications of bringing in additional services to deliver an innovation project service.

3.9 Response Effectiveness: All System Types

A comparison of overall system response effectiveness gives a clear illustration of the most successful system types over the year 2021. Of all energy diverted, the vast majority was delivered by the aggregated HSO heat load, Sunamp Type 2 and Lithium Balance systems. Indra EVSEs delivered some response throughout the measurement period, but this was inconsistent and far less than the total possible response had systems been able to communicate correctly and 'boosting' behaviour avoided. Sunamp Type 1 systems began to perform well very late in the project, and unfortunately there have been almost no wind turbine curtailment events since that time to illustrate these improvements. Finally, Type 3 and Trakm8's systems were not able to contribute to curtailment mitigation during the project.

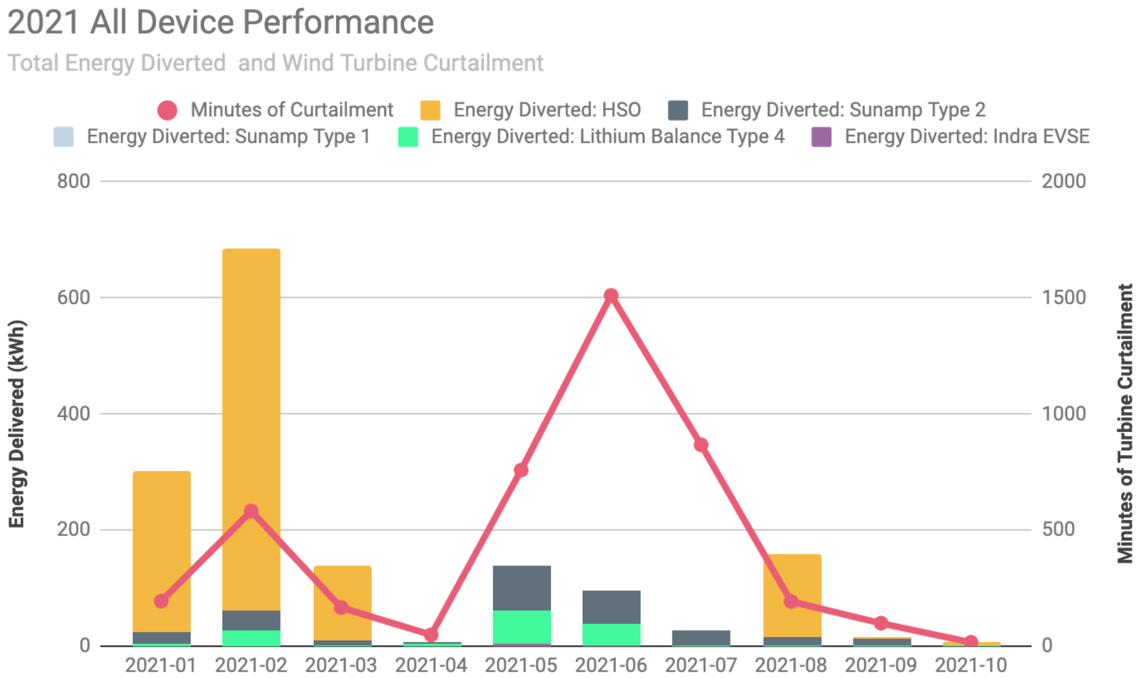


Figure 45: Curtailment and all types Response

Comparison to the total minutes of curtailment is instructive, as it shows the wide variance between different months. May, June and July exhibited significant periods of curtailment, while opportunities between August and October were far fewer. The degree to which devices responded follows the total curtailed time to an extent, with device specific factors such as system connectivity accounting for the deviations from this pattern.

A worthwhile comparison is the maximal curtailment performance had all systems installed been fully functional for the duration of 2021. While the methodology used for calculating these maximal performance figures varied slightly by device type, they take into account the import power rating of each device and its availability at the time a curtailment event took place, while assuming internet connectivity and ability to respond in a timely manner.

As an example, if a curtailment event lasting exactly one hour took place on a night where one vehicle was connected to an Indra charge point (with a 7kW rating), we valued the maximum energy as 7kWh. If however there were no vehicles connected at the time of this event, the maximum energy data would not include this event.

Similarly for a heating system (e.g. Sunamp type 1) an event would only be included if it took place at a time when a participant's tariff allowed us to charge the heat battery. A daytime event would therefore be excluded if the participant used an economy 7 type tariff, though an event overnight would be included.

The results of applying this counterfactual methodology are illustrated in the figure below. In this scenario, total response is almost entirely dictated by the total time spent in curtailment events each month.

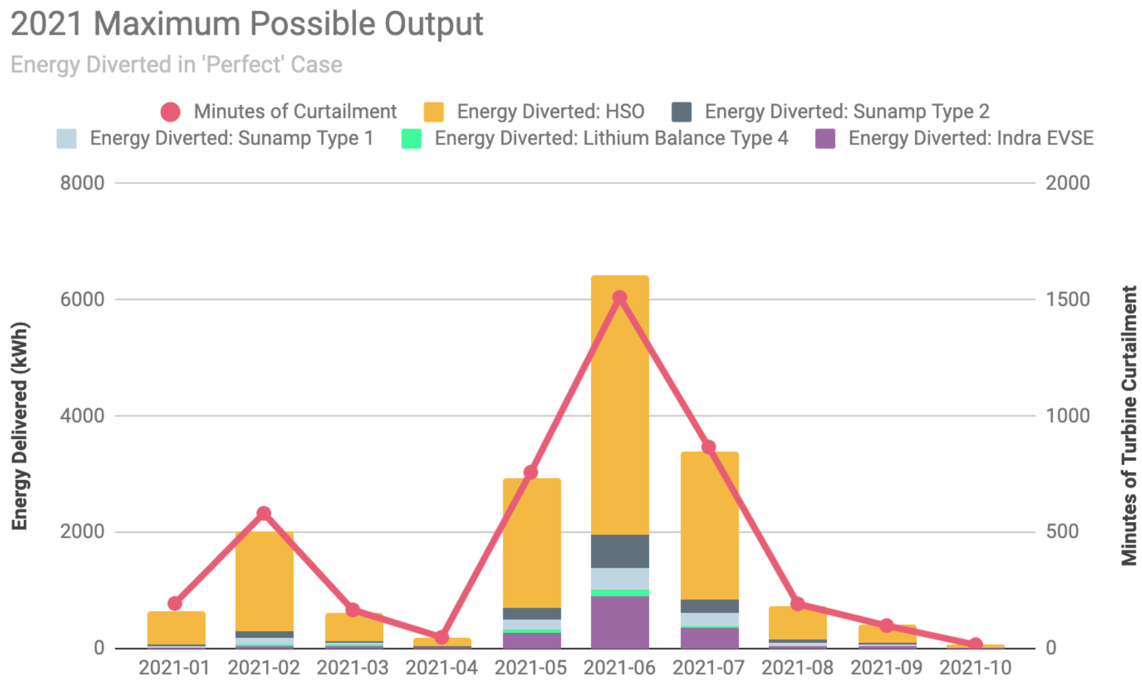


Figure 46: Curtailment and maximum possible output, all devices

As a final note on these figures, 2021 has been selected to illustrate the performance of all system types as it represents the period in which most systems were in operation, offering clearer side-by-side comparisons. Data has been collected throughout 2020, but with fewer devices and system types online it has been excluded from reporting.

3.10 Learnings: All System Types

Learning outcomes specific to each system type have been detailed in previous sections. Here some overall themes are discussed which may serve as guidance for the planning and implementation of similar future initiatives requiring the deployment of demand-side flexibility.

Each of the system types installed for the SMILE Orkney project have demonstrated an ability to absorb excess energy during wind turbine curtailment. The breadth of different technologies able to contribute to solving the challenges of flexibility in our energy system, from electric vehicles to heating systems, is a striking and positive outcome of this project. As these technologies become more mature and their usage standardised, there will increasingly be opportunities to mitigate or solve problems like wind turbine curtailment. Smart electric heating systems in particular are at a very early stage of commercially mature deployment, but it is clear that as we take on the challenge of decarbonising heat and transport over the next few years - early learnings from projects like SMILE will be significant in understanding how we can use such resources at scale to manage grid issues and increase renewable energy penetration.

There have however been significant challenges faced in the installation, management and control of these systems, and while each has been proven, the extent to which energy was diverted by each has varied widely. The aims of this project were very ambitious, and focus was split between many novel system types, each bringing its own set of challenges. Designing new heating systems which combine technologies from multiple manufacturers is hugely complex, and the more complexity introduced the greater the likelihood of installation and support issues. This was exactly what was observed during the Orkney project, and we would encourage others to build on the legacy of SMILE and other pioneering efforts in the electric heat space and consider the learnings and recommendations from this project when designing their own project aims.

To maximise the chances of successful implementation, a smaller number of system types with greater numbers of each offers the best opportunity. In particular, extending the period of workshop testing before home installation is strongly recommended; only when a system type is proven in a controlled environment is it likely to be ready to be installed in a real home - although it would have been difficult and expensive to faithfully replicate and validate before final physical installation, the various home configurations encountered over the course of the project. Even with sufficient pre-installation testing, a very slow roll-out of assets, where each installation only commences when the previous is confirmed to be fully operational is the approach which the SMILE Orkney partners would advocate. Furthermore, in locations such as Orkney, properties can vary greatly; presenting unique challenges/learning potential from each. A slower installation period would allow for the absorption of such learnings prior to advancing. However, installing project equipment across the breadth of construction types found in the Orkney project area accelerated and maximised the possible learnings for the project reporting.

While longer turbine curtailment events did take place, marginal curtailment periods tend to be short, often lasting between a few seconds and a few minutes. Analysis of the power response of devices indicated that a significant improvement in energy diverted during curtailment events could be achieved if device latency was reduced. While device response times varied, a preliminary ex-post theoretical analysis showed that reducing this delay by 30s could have improved the energy response during periods of marginal curtailment by 38%.

The impact of the pandemic on the project cannot be overstated. Diminished access to sites, and the inability of many partners to physically attend to their systems has made the challenges of troubleshooting many times more difficult to resolve. The rate of progress from mid-2021 onwards in terms of new systems being made operational could have been seen much earlier had COVID-19 not prevented face to face work. As previously mentioned, the type 1 and type 2 system require onsite visits in order to complete firmware updates. The reduced capacity to have engineers onsite during the pandemic lockdown made updating and testing software significantly harder and delayed.

While the SMILE Orkney project has demonstrated some of the possibilities for the use of smart, connected devices in meeting the challenges of a renewable-powered energy system, and has helped make a start in understanding commercial viability of such products - it has also highlighted the importance of business models and market mechanisms and constructing propositions to create sufficient incentives for the uptake of such hardware so as to alleviate their high capital costs. This is particularly applicable to storage solutions such as Lithium Balance and Sunamp. In both cases, storage was used primarily for the dispatch of energy during curtailment events and potential business cases and models were investigated in the framework of the project by considering the different stakeholders involved.[1]

The project partners went to great efforts to ensure the heat pumps (where installed) made up the majority of the hot water generation, compared to using less efficient resistive heating. However, the heat pump is significantly less effective in matching curtailment events. The heating elements in Sunamp PCM heat batteries, hot water cylinder immersion elements, and charging of lithium Ion batteries make for very effective instantaneous response to curtailment matching. But in the case of the PCM heat batteries and immersion elements, these can result in roughly 3x more expensive hot water, compared to that generated through an ASHP. The HSO assets brought in a demonstration of an effective rebate system which compensated for the use of the less efficient electrical loads.

3.11 Cost Analysis - Smart Heat System Types

While the scope of this report is focused primarily on the effectiveness of various smart heat and other systems to increase consumption of locally produced renewable energy, it is important to remember that for the smart heat customers this also represented a change in how their home heating needs were met.

One of the objectives of the SMILE project was to demonstrate cost reduction in heating system operation with a goal of 10% reduction in £/kWh delivered heat across all types. A primary factor contributing to setting this a priority target was that the heating systems installed consisted in most cases of ASHPs which are typically more energy efficient systems with a high coefficient of performance (CoP).

In reality the observed impact of the project on heating costs has been mixed between the systems installed. Some observations for participants switching from non-electric heating to SMILE smart heat system types and for whom sufficient home energy usage data was available (sample size of 14) are summarised below:

- Half the participants experience heat energy cost reduction, while the other half experience an increase

[1] D6.6 SMILE business cases and financial mechanisms

- The cost change ranges from a £/kWh reduction from 18% decrease in cost to 36% increase in cost
- On average, participants experienced a 5% increase in £/kWh cost

The average increase observed could be explained by a number of things such as: potential overall lower outside temperatures than expected (impacting the ASHP CoP); poor ASHP timer management, which could result in poor performance of the heating system, increase home heating energy consumption due to COVID-19 induced lockdowns, as well as increase in overall UK electricity costs over the period of the project.

There are a few reasons to be wary of drawing too many conclusions from this analysis, including:

- Insufficient data or gaps in energy usage for different households, which resulted in having to restrict the study to 14 participants only;
- Insufficient data to draw conclusions per install type as this would make the sample even smaller;
- Figures obtained were based on only one year of data collected pre and post SMILE, which makes it difficult to clearly isolate the factors driving a difference in energy usage behaviour especially in the face of extrinsic factors such as: lower outside temperature from one year to the next, higher occupancy and therefore increase home heating energy usage due to COVID-19 induced lockdowns etc.;
- The assumptions taken on different devices' efficiency might not be fully representative of actual observed efficiency at participant premises;
- Heating related electricity usage was not disaggregated from the rest of home electricity usage for properties from which bills were used for the analysis. For properties switching to electric heating, it was assumed that non-heat related electricity usage was constant pre and post SMILE to calculate overall energy output post SMILE introducing potential inaccuracies in the analysis - exacerbated by factors such as COVID-19 induced lockdowns;
- Householders' situation and behaviour may have changed over the course of project period, which is difficult to account for;
- UK electricity costs have changed significantly over the past few years which has a big impact on participants' heating costs. It was observed that participants often remained with their electricity provider rather than prioritising electricity price competitiveness; and
- Assumptions had to be made around participants' pre-SMILE oil consumption based on their oil refill data rather than actual consumption data.

For future projects trying to leverage the learnings from this project, below are some suggestions to mitigate encountering issues described above when conducting a participant cost analysis

- Conduct at least two years of energy monitoring before after system install, specifically with disaggregated heat and non-heat related electricity consumption;
- Push and demonstrate the importance of switching to cheaper electricity tariffs to reduce electricity bills;
- Deploy more installations for fewer installation types, so as to increase the sample per install type;
- Test different heating strategies (different space heating time management) across the system;

- Deploy heat meters to monitor the actual efficiency that the systems can achieve;
- Analyse the data within the context of variable outdoor temperatures.

4 Conclusions

Each of the system types installed for the SMILE Orkney project have successfully demonstrated the ability to absorb excess renewable energy that would have otherwise been curtailed. Even considering the relatively small scale of the project, the potential positive impact on decarbonisation of heating and transport from deploying such solutions at scale is significant and can be seen clearly.

In particular, the smart electric heating systems - such as the ones used in the project - are still in early stages of commercially mature deployment, and the project has proven how they can be a significant resource for grids across the world to manage flexibility issues. The project also demonstrated how very different configurations of smart electric heat can be used for such use cases and offers an early blueprint for equipment manufacturers on how they can factor in the capabilities required for such flexibility applications.

The use of electric vehicles to manage grid flexibility issues is an increasingly important area of innovation, and the project demonstrated yet another use-case for that.

The learnings from this project can be used as a springboard for further commercial innovation in the smart electric heat and electric vehicle flexibility space, including innovation in end customer value proposition that will incentivise uptake of such products.

While the issues observed during the project - such as reduced curtailment activity from the Eday turbine, connectivity issues with devices and inability to, pre-installation, test for and mitigate issues observed in the field - may have dampened the impact that could be directly observed during the project, they are very valuable learnings that can built on for future innovation projects in this space. They also offer equipment manufacturers and renewable generation operators early insights into how they can innovate using cutting edge technologies to produce future revenue streams.