My Electric Avenue (I^2EV)

SDRC 9.7.1 Impact of Esprit on Heat Pumps

Supporting documentation

Author: EA Technology

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The 'My Electric Avenue' project is the public identity for the Low Carbon Networks Fund Tier 2 project "I^2EV." The formal title "I^2EV" is used for contractual and Ofgem reporting purposes.

Project leads

Project partners

My Electric Avenue has received support from Ofgem through the Low Carbon Networks (LCN) Fund.

Version Tracking

Date	Version	Author/s	Notes	Reference documents
06/03/2015	0.1	ES		The effects of cycling on heat pump performance https://www.gov.uk/government/publications/heat-pump-performance-effects-of-cycling

Final Approval

Date	Version	EA Technology authorisation by	SEPD authorisation by
12/06/2015	Issue 1	Duncan Yellen	
26/06/2015	Issue 2	Duncan Yellen	Nigel Bessant

Executive summary

This report provides recommendations for cycle times when Esprit is applied to domestic heat pumps based on dialogue with heat pump and compressor manufacturers during February and March 2015, and a review of a previous EA Technology investigation into heat pump cycling.

Esprit implements Demand Side Response (DSR) by direct control and 'cycling' of loads. The control algorithm curtails (switches off) the power supply to individual loads in order to prevent these from consuming electricity at times when the demand on the network is above a certain threshold.

Cycling for the purposes of DSR has a varying degree of impact on the end functionality, and hence the user, depending on the type of installation: space heating/cooling or water heating/cooling.

Of 10 heat pump manufacturers contacted, two manufacturers recommend against removing power from the units, but suggested the units could respond to signals from Esprit to control the output, without removing power altogether.

On the basis of the features and evidence summarised within this report, the power supply should be curtailed with a:

- Minimum off time, to protect the compressor
- Maximum off time, to ensure sufficient heating
- Minimum on time, to protect the compressor, avoid adverse cycling effects on efficiency and to ensure sufficient heating

The following indicative restrictions on heat pump cycle times are proposed:

- **Minimum off time: 3 minutes**
- **Minimum on time: 15-30 minutes**
- **Maximum off time: 60 minutes**

It should be noted that these figures are initial estimates only, and would require adjustments following more extensive investigations and studies.

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1 Introduction

The My Electric Avenue (MEA) team requires evidence regarding the impact of Esprit control and cycling on the effectiveness and performance of heat pumps for the project SDRC 9.7, specifically providing:

- "Views of the OEM [Original Equipment Manufacturer] community of the impact (if any) that cycling of Electric Vehicles (or Heat Pumps) may have on their product(s) and end of life"
- "Recommendations of suitable cycle times for Electric Vehicles (and possibly Heat Pumps) for demand-side response"

This report outlines such evidence obtained from dialogue with heat pump and compressor manufacturers during February and March 2015, and with a heat pump expert within EA Technology alongside a review of a previous EA Technology investigation into heat pump cycling. On this basis, high level recommendations are made for cycle times when Esprit is applied to domestic heat pumps with a focus on heating.

1.1 Esprit 'cycling' of loads

Esprit implements Demand Side Response (DSR) by direct control and 'cycling' of loads. The control algorithm curtails (switches off) the power supply to individual loads in order to prevent these from consuming electricity at times when the demand on the network is above a certain threshold. During such times, loads are cycled on and off to ensure that the end devices receive some power periodically, which means that the power supply to individual devices may be switched off for a sustained length of time interspersed with brief periods of restored power (on a scale of minutes).

Curtailing end use devices in this manner, and cycling them so that their power supply is repeatedly switched on and off, must be done in a sympathetic manner. The curtailing and cycle times should ensure that the device:

a) remains capable of performing its function to an acceptable standard

b) is not adversely affected in terms of its internal performance and end-of-life

This report investigates these two considerations for heat pumps, and then recommends cycle times for the Esprit DSR algorithm.

2 How Heat Pumps are affected by Cycling

Heat pumps utilise air or low grade heat from the ground to produce space and hot water heating, and can also be configured to produce space cooling (air conditioning). The heat pump itself can be installed as part of a range of different types of space and water heating arrangements, including those listed below for typical UK domestic uses (for brevity, non-domestic uses are not considered in this memo). Cycling for the purposes of DSR has a varying degree of impact on the end functionality, and hence the user, depending on the type of installation:

2.1 Domestic heat pumps – space heating/cooling

- **Retrofitted heating systems with heat pumps typically use radiators**, and look likely to take off as a larger share of the market. Space heating is then very closely linked to the output of the heat pump at that specific time; if the heat pump is curtailed for any extended period of time, the end user is likely to notice a drop in indoor temperature.
- **New builds with heat pumps are often designed with underfloor heating**, where a lower grade heat is used and the floor will effectively store heat for a period of time. The heat pump could therefore be curtailed without a significant impact being felt by the user for some time.
- **Heat pumps can be installed in conjunction with thermal storage** as a setup specifically intended for DSR applications. The storage effectively decouples the heat pump operation from times when the heat is needed, which allows the heat pump to operate outside of those hours and potentially at night. It could therefore be curtailed for longer peak periods without substantial impact.
- **Hybrid installations combine a heat pump with a gas boiler**, such that the gas boiler produces heat when the heat pump is not able to. Under these circumstances, curtailing the heat pump effectively moves the heating load to the gas network and the customer is affected only in terms of the resulting changes in cost.
- **Domestic air-conditioning is a rare application in the UK**. Additionally, it is typically required in the summer when load conditions on the network are typically well below a level where Esprit may need to shed load. It is therefore not included for consideration in this memo.

Heat pumps are typically sized in accordance with the heat loss of the property, in such a way that they are just able to meet the peak heating demand during the coldest part of the year. Under those conditions, the heat pump may be operating flat out at times of peak network load, which means the effects of curtailment would be noticeable by users with retrofitted heat pump radiator systems. Their average indoor temperature would be reduced dependent on the total amount of time that the heat pump is switched off for (the relationship depends on the thermal mass of the house), and could drop noticeably if the device is offline for a sustained period depending on the type of installation.

Finally, it should also be noted that many heat pumps are currently supplied with electric booster heaters. These are designed to support the heat pump when additional heat is required. Esprit would be likely to curtail heat pumps during a cold spell, when load is likely to be high on the network and thermostats may be set to provide a high degree of space heating. Once the heat pump is allowed to switch back on, the booster heater may kick in to bring the space heating back up to the required level. This would then cause a higher peak in the electricity demand, potentially counteracting Esprit's intended functionality.

2.2 Domestic heat pumps – water heating

- **Heat pumps can provide both hot water and space heating**, although during operation they supply one or the other rather than both simultaneously. Hot water heating by the heat pump is typically provided in conjunction with a hot water tank. The effect on the user when the heat pump is curtailed therefore depends on the pattern of their water usage and any timers used to maintain a hot water supply during certain parts of the day only.

- **Many properties with heat pumps use a standard electric immersion heater for hot water heating**. Under these circumstances, curtailing the heat pump has no effect on hot water provision.

The key component of a heat pump from a DSR perspective is the compressor. It is connected to the electricity supply and controls how much heat is produced by the heat pump, and when. The effects of cycling on compressor performance depends on whether it is of a fixed or variable variety, as described below.

In simple terms a heat pump consist of an evaporator, a compressor and a condenser, and liquid is passed between these components at different temperatures as shown in Figure 1. Low-grade heat input to the evaporator is provided either by air for air source heat pumps, or ground heat for ground source heat pumps. The compressor consumes electricity to create the increase in temperature level of the heat that is outputted by the condenser for space heating and water heating. For space cooling (air conditioning), the process is similar but outputs coolth[1].

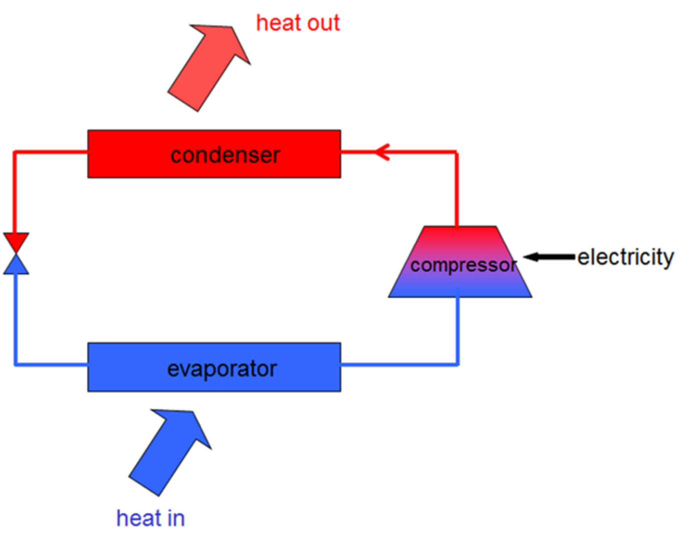

Figure 1 – Diagram representation of components in a heat pump

When cycling a heat pump, Esprit would interrupt and restore the compressor's power supply. This causes the heat pump to stop outputting heat (or coolth) into the space heating or water heating system connected to it, affecting the end functionality. It is also the compressor unit that would be most affected in terms of efficiency and end of life.

[1] Coolth is terminology commonly used by building service engineers and is literally the opposite of heat. Adding energy to a system results in heat and removing energy from a system results in coolth.

Two main types of compressors are used in heat pumps today: fixed speed and variable speed. Fixed speed compressors are common in many existing designs, but the variable variety is increasing in use for air source heat pumps in particular. These two types present different electricity demand patterns on the network as shown in Figure 2:

- **A fixed compressor** is either ON or OFF, and consumes approximately a fixed amount of electricity when ON in order to produce the higher grade heat (the compressor power is also affected by the source and sink temperatures). The heat pump goes on and off as needed, in order to keep the space or water heating at the required level. Demand patterns of fixed compressors therefore have a square wave characteristic, where the frequency and duration of ON periods depend on the heat pump design and the heating requirements. During a very cold day, the ON period may extend across the whole day, while a mild day might just see a few brief ON periods to top up the hot water supply. Curtailing a fixed compressor effectively shortens the present ON period and/or delays the onset of the next one; once the compressor is allowed back on, this may be followed by a longer ON period to compensate, if needed, which means that the electricity demand has effectively been delayed in time (although this may be distorted by a spike in demand from a connected booster heater, as mentioned above).

- **A variable compressor** typically consumes electricity continuously when heating is required, and varies the power consumption and related heating output to match changes in heating requirements. Demand patterns of variable compressors therefore have a smoother characteristic with a variable magnitude. During a very cold day, the demand may be at a continuous high level, while a milder day may see a low level demand and periods of no demand at all. Curtailing a variable compressor abruptly brings the supply to zero. Once the device is allowed back on, this may be followed by a higher power consumption level than before (by way of compensation), in which case the electricity demand is not delayed in time quite as effectively.

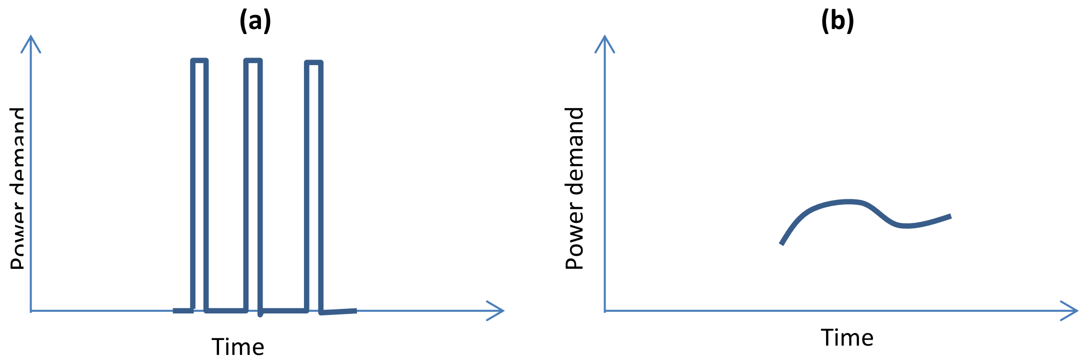

Figure 2 – Nature of power demand from (a) fixed compressors and (b) variable compressors

In both cases, the impact of cycling on heat provision ultimately depends on the type of installation (as described above), the temperature requirements at the time, and how soon the heat pump can begin operating again to bring the service back to the intended level.

However the compressor performance can also deteriorate in the long-term from particular patterns of cycling. 'Short cycling' is a known problem for heat pumps in a non-DSR context, where temperature control systems may cause the heat pump to frequently cycle on and off even though the power supply remains available (this applies particularly to fixed speed compressors, as the variable variety is theoretically capable of reducing its output to avoid the worst excesses of cycling). A short running time can affect the internal motor and oil flow, causing problems such as motor burn or lubrication failures, and ultimately a fault in the heat pump operation, particularly if this happens on a frequent basis. Cycling that is applied by Esprit, by cutting and restoring the power supply, is likely to be subject to similar implications and considerations.

3 Evidence from OEMs and industry experts

The following sources are used as evidence in this report:

3.1.1 EA Technology report for DECC 2012

A report by EA Technology entitled "The effects of cycling on heat pump performance", previously submitted to DECC in November 2012 (https://www.gov.uk/government/publications/heat-pump-performance-effects-of-cycling), describes how fixed compressor heat pumps are impacted by short cycling instigated by Thermostatic Radiator Valve (TRV) temperature controls. Evidence was gathered through practical trials in the EA Technology test houses, as well as from experts and manufacturers, as outlined in its supporting documentation. Key findings and evidence can be summarised as:

- The report finds that run times shorter than 6 minutes have a "detrimental effect on the energy performance" particularly in air source heat pumps, but also in ground source heat pumps to a lesser extent.
- Specifically, heat pump and compressor manufacturer Danfoss indicated that the heat pump should experience no more than 12 starts per hour, with a recommended 3 minute time-out between starts.
- The compressor manufacturer Copeland (Emerson) indicated that the number of starts should be limited to 10 per hour. They also stated that "There is no minimum off time because scroll compressors start unloaded, even if the system has unbalanced pressures. The most critical consideration is the minimum run time required to return oil to the compressor after start-up."

3.1.2 Dialogue with heat pump and compressor OEMs in February/March 2015

The MEA team has approached heat pump and compressor manufacturers to request input to this memo, as outlined in "86002_HeatPumpManufacturersResponse_20150-03-06_v0.1" (see latest version). Key input obtained to date can be summarised as:

- Compressor manufacturer Emerson, via Director Integrated Solutions Dr Eric Winandy, indicated that there would be no impact of a DSR technology such as Esprit provided that their guidelines are respected. Their design is done such that the compressor is able withstand a fair amount of stop/start, beyond which performance and reliability will be affected: the minimum on time should be above 3 minutes to allow stabilization of the system, and the maximum frequency for switching the heat pump on and off should be 10 times/hr as per their guidelines.

- Swedish heat pump manufacturer NIBE, via David Kroon in Strategic research / Product management, provided useful information on how Esprit might best be integrated with heat pumps. They reported that they don't recommend that heat pump units have their power supply switched on and off in the way that Esprit currently implements DSR. Although they can't say exactly how it will influence the life time of the unit, they can only say that it has a negative impact. Beyond the life time issue, there are also important security functions that require constant power supply to the control system. Also, the heat control of the building would be affected, as it depends on the control system which would be restored each time the power supply is restored, causing some delays in the heating control. NIBE also indicated that if power supply to variable inverter-controlled compressors is cut, this may not be ideal as "the ramp up and down of the inverter compressor during start and stop should be kept".

- Instead, NIBE strongly prefer DSR implemented as via tariff control; today they have the capability to stop the compressor and if applicable the electric back-up in response to signals received by the heat pump. In this way, they don't need to switch off the complete unit, so the control device could still be active, which means security and heating control could work all the time. Normally that type of signal comes from the grid owner and is possible with a wire from e.g. the electricity meter to the heat pump. It could also be possible to have communication via internet, if the heat pump is connected to the internet. Therefore, rather than incorporating a DSR-type control device in the heat pump to control the power supplies of only the compressor and the back-up electric heater (which would cause complications in installation and integration within the product), NIBE would prefer letting the heat pump make a controlled stop and start in response to control signals from Esprit. That is, Esprit would be implemented in a similar manner that tariff signals are implemented today. NIBE stressed that they see a great opportunity for heat pumps to play a part in the smart grid and DSR systems in this manner.

4 Recommendations for heat pump cycle times

Recommendations for suitable Esprit cycling times for heat pumps are expressed as shown in Figure 3. On the basis of the features and evidence summarised above, the power supply should be curtailed with a:

- Minimum off time, to protect the compressor
- Maximum off time, to ensure sufficient heating
- Minimum on time, to protect the compressor, avoid adverse cycling effects on efficiency and to ensure sufficient heating
- Maximum on time not required

As outlined in the section above, if Esprit implements direct control by curtailing the heat pump power supply, compressor protection is likely to require a minimum on time (to allow the motor and oil systems to stabilise). There are also indications that a minimum off time may be required to ensure that short on-times don't occur too frequently.

From a heat provision perspective, a maximum off time and minimum on time form the key considerations. Heat pumps must receive a minimum amount of access to power over a certain period of time, to ensure that they are able to perform their overall heating function to an acceptable standard. The equivalent requirement for electric vehicles – as trialled in the MEA project – reflects the need for the car to have accumulated sufficient charge by the time the user intends to take it for a drive. For heat pumps, this consideration is slightly different as it is often necessary to sustain an acceptable temperature *throughout* a period rather than just at the end. Depending on the availability of thermal storage and alternative heat supply in the heat pump installation, the temperature will drop at a certain rate over time when the heat pump is not in operation. A maximum off time will ensure that this does not drop too far on individual occasions. That given amount of curtailment may then need to be followed by a minimum on time of power availability, to ensure that temperature does not fall too far over time.

A maximum on time is not needed, of course, as this would correspond to the normal non-DSR condition where the heat pump has continued access to its power supply.

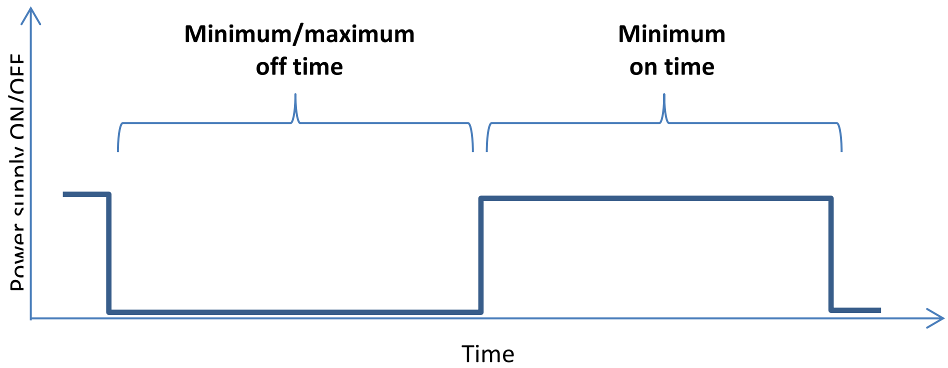

Figure 3 – Minimum/maximum off times, and minimum on times, of cycling patterns applied to a heat pump power supply

4.1 Minimum off and on times to protect compressor

For the purposes of a technology like Esprit, the evidence above indicates relatively clearly that there are requirements on a minimum on time. As an initial recommendation, a 6 minute minimum is proposed on the basis of the EA Technology report, which is also in line with a maximum of 10 starts per hour.

The requirements for a minimum off time are a lot less clear. The need to restrict the number of starts in an hour to 10 (taking the more stringent of the two reported figures) suggests that each complete ON/OFF cycle as drawn in Figure 3 should take at most 6 minutes. If the ON portion of the cycle is allowed to be as low as 3 minutes, as per Emerson's recommendation above, then the OFF portion of the cycle must also be at least 3 minutes in order to ensure higher frequency switching doesn't occur. This indicates a minimum off time of 3 minutes. However, the overall findings in the EA Technology report indicate a minimum 'run-time' of 6 minutes. If this is taken to mean a minimum on time of 6 minutes, there is no need to refine a minimum off time in terms of meeting the 10 starts/hour restriction. Furthermore, Emerson (Copeland) had explicitly stated that no minimum off time is required, while Danfoss indicated a 3 minute timeout between starts (although it is unclear how to interpret this statement).

In the interest of taking a conservative approach, and given that it is unlikely to place any significant limitation on Esprit, the recommendation proposed in this memo is to note a minimum off time of 3 minutes. It should also be noted though that this figure does not account for how the on/off events forced by Esprit might interact with on/off events instigated by the heat pump itself in response to temperature control.

In summary, the recommendation is:

- Minimum on time of 6 minutes
- Minimum off time of 3 minutes

4.2 Maximum off times and minimum on times to deliver sufficient heat

The effects of off and on times on a heat pump installation's ability to deliver sufficient heat is a complex matter, as indicated in the sections above, and would require careful modelling and trials to fully establish. It depends heavily on the thermal properties of the building itself, weather conditions, and on whether thermal storage and secondary heating systems are available. Retrofitted heat pump systems that use radiators, without any further equipment, are the most sensitive to curtailment during peak hours. On that basis it is sensible to use them as basis for worst-case requirements on cycling settings, particularly as they might ultimately form the largest portion of the market.

Radiator-based heat pump systems must produce heat at the same time as it is needed, and their demand is likely to coincide with times of peak network load in the morning and evenings during the colder parts of the year. Here, it is assumed that heating requirements might extend for 4 hours in the morning and 6 hours in the evening. These figures are only used here as an example, and may need to be considered to be longer, in order to account for the fact that heat pumps often require longer 'pre-heat' periods as they have a relatively low heat output compared to a boiler system. Some installers recommend that heat pumps are left running 24/7.

The maximum off time should reflect the largest acceptable continuous drop in temperature during cold mornings and evenings. Without further evidence, an initial approximation might be 1 hour, although this is likely to be on the longer side and ultimately a shorter period may be required. On a cold day, this would be noticeable in most properties depending on their heat loss properties. A 15 minute off time would be barely perceptible.

The minimum on time should reflect the largest acceptable drop in temperature overall during the morning and evening. That will depend on the maximum off time above, as well as the heat pump's capacity to then restore temperature on a cold day. If outside temperatures are extreme and the heat pump was already operating flat out in order to maintain the original temperature level, it may be unable to recover following a 1 hour curtailment (even with a built-in booster heater), resulting in a permanent drop of a few degrees throughout that day. A minimum on time of at least 30 minutes would likely be required to ensure the temperature does not drop too far during the 5 hour evening period. However, on most days during the colder part of the year, the heat pump would have some spare capacity available. In this case a sustained ON period (with a fixed compressor) or higher output (with a variable compressor) following the curtailment can restore the temperature up to the original level. A 15 minute minimum on period may be sufficient to achieve this or close to it.

This discussion provides an initial high-level indication only, and would need to be refined by substantial further studies and thoroughly trials. On that basis, the following are recommended:

- Maximum off time of 60 minutes
- Minimum on time of 30 minutes on very cold days, and 15 minutes on cold days. This supersedes the 6 minute requirement of the compressor.

Types of heat pump installations with thermal storage and secondary heating are likely to be substantially more resilient to curtailment during network peak hours. It may be possible to design Esprit in such a way that the type of heat pump system is accounted for, allowing radiator-based heat pumps to remain on for longer on very cold days as needed.

5 Summary

In summary, evidence collected to date suggests the following indicative restrictions on heat pump cycle times, on the basis of radiator-based installations:

- **Minimum off time: 3 minutes**
- **Minimum on time: 15-30 minutes**
- **Maximum off time: 60 minutes**

It should be noted that these figures are initial estimates only, and would almost certainly require adjustments following more extensive investigations and studies. A less restrictive set of figures would likely be appropriate if considering heat pump installations that are more resilient to DSR, such as those with thermal storage or back-up boilers.

This report has also highlighted additional considerations for Esprit applied to heat pumps. These include the potential counter-actions by electric booster heaters, and the potentially favourable option to interact with heat pumps via control signals similar to tariff signals rather than directly control the power supply.

Appendix A. Project Memo

M E M O

To: MEA project team

From: Ellin Saunders, EA Technology

Date: 6 March 2015

Subject: Heat pump / compressor manufacturer responses re the impact of Esprit cycling on equipment functionality and end of life

The My Electric Avenue (MEA) team requires evidence regarding the impact of Esprit control and cycling on the effectiveness and performance of heat pumps for the project SDRC 9.7, specifically providing:

- "Views of the OEM [Original Equipment Manufacturer] community of the impact (if any) that cycling of Electric Vehicles (or Heat Pumps) may have on their product(s) and end of life"
- "Recommendations of suitable cycle times for Electric Vehicles (and possibly Heat Pumps) for demand-side response"

This memo outlines the requests for advice that have been sent by the MEA team (Ellin Saunders) to heat pump and compressor OEMs, and includes copies of the complete responses received to date. It is anticipated that this memo will be updated as additional responses are received.

Requests for advice

An email was sent to OEMs of both heat pumps and compressors to request advice on a number of specific issues relating to heat pump curtailment by Esprit (see typical sample in Figure 4: Sample email sent to heat pump and compressor OEMs.). The compressor is the component within the heat pump whose power supply is curtailed by Esprit and consequently is most affected by interruptions; compressor manufacturers were therefore included alongside heat pump manufacturers.

Individuals within companies were contacted by making use of contacts of EA Technology staff (Rob Green, NET team) and Dr Penny Dunbabin (DECC), as listed in Table 1.

Company	Date	Any response	Response complete
Emerson (compressors)	25/02/2015	✓	✓
Danfoss (compressors, heat pumps)	25/02/02015	✓	
	26/02/2015		
NIBE (heat pumps)	25/02/2015	✓	✓
	02/03/2015	✓	
Ice Energy (heat pumps)	25/02/2015	✓	
	26/02/2015		
Calorex (heat pumps)	25/02/2015		
TEV (heat pumps)	25/02/2015		
Stiebel Eltron (heat pumps)	25/02/2015		
Kensa (heat pumps)	25/02/2015		
Mitsubishi (compressors?)	25/02/2015	✓	
Daikin (compressors?)	25/02/2015		

Table 1 – OEMs contacted for information

Dear Dr [redacted]

I'm writing from EA Technology, a power engineering consultancy, to ask for Emerson's view on how heat pump compressors are affected when their power supply is cycled on and off for the purposes of Demand Side Response (DSR). Rob Green here at EA Technology gave me your contact details and suggested you would be a very knowledgeable person to speak to.

We are compiling a brief high level report on the impact of such cycling on a heat pump's performance and end-of-life, and are gathering evidence from industry for this purpose. We'd greatly appreciate your input which would, with your permission, contribute towards official evidence in a project on direct control DSR funded by Ofgem (http://myelectricavenue.info/: the trials in this project focus on electric vehicles, but the control technology could also be applied to heat pumps.)

Specifically, the DSR system in question 'curtails' - i.e. switches off - the power supply to individual heat pumps when the load on the local network is high. The system may then periodically switch the power back on for brief durations during such curtailing periods, to ensure that each user receives some power rather than none. We will produce indicative recommendations for appropriate cycle times of heat pumps (in terms of switching their power supply on and off in this manner), such that the heat pumps maintain their ability to produce heat/coolth satisfactorily and such that the equipment doesn't suffer in terms of efficiency or end of life.

We would therefore value your professional views on the following questions, for fixed/variable compressors of different sizes:

1. *How is the heat pump/compressor's performance and end-of-life affected by periodically switching off the power supply, at different frequencies and different lengths of time?*
2. *What would be your recommended minimum duration for switching off power to the heat pump (and then allowing it to resume again)*
3. *What would be your recommended maximum frequency of cycling the heat pump on and off (for example, how many times within an hour)*
4. *Does the heat pump/compressor have phases of operation where switching off the power supply is particularly damaging or has no impact?*
5. *How would these answers change if the control reduced the power to the heat pump rather than switched it off completely?*

I hope that this information is sufficiently clear, and would appreciate you taking the time to advise us. If you are able to respond within the next few days, that would be particularly useful.

I look forward to hearing from you!

Best regards,

Ellin Saunders

Figure 4: Sample email sent to heat pump and compressor OEMs.

<u>Copies of complete responses received to date</u>

This section has been removed from this publicly available version of this report due to it containing details of private individuals.