Measurement of the capacity of a freezer for active demand side management

Bert P. Vande Meerssche, Geert Van Ham, Geert Deconinck

***Abstract*— Because of the intermittent character of renewable energy sources, there is a need to implement buffer capacity in the electricity grid. Active Demand Side Management, which controls the energy consumption of electrical loads distributed in the grid is a promising way to achieve this buffer capacity. This paper discusses the research on the buffer capacity for a domestic freezer in view of using it in an active demand side management strategy. The dynamic characteristic of a freezer has been measured by monitoring temperature and energy consumption in an acclimatised room. The measurements consider a number of parameters like filling degree, ambient temperature, setpoint of the freezer and consumer behaviour. From the measurement results a model of the freezer has been built. As a case study, this model has been used to evaluate financially and energetically the use of the buffer capacity of the freezer in a day/night control strategy.**

***Index Terms*— active demand side management, renewable energy sources, smart grid.**

I. Introduction

WORLDWIDE people are becoming aware that fossil energy sources are scarce[1] and that the use of them emits CO_2, possibly causing “global warming” by its green house effect. To achieve a durable energy supply without compromising next generations, a transition to more renewable sources is necessary.

An additional advantage of RES is that they are often distributed which results in a reduction of transmission and distribution losses. A serious disadvantage (for small as well as for large installations) however is the intermittent character of the renewable sources. You cannot control the sun or the wind. For the moment this intermittent character is compensated by traditional central fossil (or nuclear) power plants. But the stability boundaries may be reached sooner than one expects [1]. Currently, the growth of renewable energy sources (RES) is exponential [2], [3]. The number of small installations will further increase (some cities like Marburg, Germany [4], oblige to install PV on new buildings) and more and more large installations are being installed [5]. For Europe, in 2008 large scale PV capacity consists of 3.5 GW [5], on a total capacity of 14.7 GW [3], whereas in 2006 the capacity of large scale installations was only 0.5 GW on a total capacity of 6.77 GW. On the other hand, with the increase of renewables, the share of fossil energy decreases and thus the reserve capacity of the fossil energy plants for frequency control also decreases. The reserve capacity of today's energy plants only allows a limited number of RES.

A solution may come from smart grids [6]. Smart grids make a decentralized control of the electricity grid possible. Because the renewable sources[2] cannot be controlled, more decentralized control on the demand side is needed. At this moment, demand side management (DSM) consists only of peak shaving, load and cost reduction, where users have to switch certain appliances on or off themselves. The appliances do not have any intelligence implemented. It is obvious that this coarse way of demand side management is not able to keep a power system consisting mainly in renewables stable. To fully exploit the potential of renewable energy sources, DSM has to be used in a more active way [7], [8].

According to a study by Capgemini [9], the potential for active demand side management (also called “demand response” or DR) is fantastic. Implementing DR, without any additional measures could achieve between 25 and 50% of the EU's 2020 targets concerning energy savings and CO2 emission reductions. Also according to this study, 72 GW of peak generation capacity, which is typically expensive and low efficient, could be avoided. To obtain these results, business as usual will not satisfy.

An accepted concept for implementing DR is a multi-agent system, driven by economic and reliability signals [10] - [14]. In [10] this concept is demonstrated by a simulation for a diesel generator feeding 50 kW critical load and 12,5 kW non-critical load. However, systematic, wide-scale deployment of it has yet to be demonstrated. The transition will be a step-change innovation [11]. In reality the generators will often be a renewable source and loads will exist of all kinds of different appliances. Loads are divided in controllable and uncontrollable loads (consumer electronics

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[1] Worldwide Fossil reserves estimations depend on the source, but the value for oil and gas varies around 60 years.

[2] CHP is often distributed but is not a renewable source and can be controlled to a certain extent.

like TV, ...). Controllable loads can have a delayed start (non-urgent loads like washing machines, dish washer, ...) or have some kind of energy buffer (storage-based appliances like cold, heat, battery) [12]. An appliance perfectly suitable for DR, is a freezer. By cooling to a lower temperature, the freezer can postpone its energy consumption for a longer time (note that a domestic freezer can typically cool to approximately -28°C).

Intelligence will be (partly) distributed in device agents that communicate with a more intelligent general agent. The general agent communicates with the smart meter and the different device agents, and determines which device can take energy at a certain time [13]. The device agent measures for example the temperature of a freezer and determines the price at which the freezer wants to buy energy. To fully exploit the buffer capacity, the device agent should not only give a price signal, but should also give a prediction for future energy consumption or production of the device [14].

It is important to note that demand response must not only be driven by economic signals, but also has to consider the needs of the grid. A local controller (as general agent) can fulfill this task. In [15] the local controller can choose between normal, emergency and island mode. In each mode the controller optimizes consumption using predictions of generation and of energy consumption.

Whereas the concept of DR is for the most part accepted, for the implementation there is a strong need for dynamic profiles (also called information models in [15]) of loads and production units to fully exploit the capacity. This paper discusses the identification of the dynamic load profile of a freezer. Although a freezer is well suited for DR, a quantitative evaluation of its buffer capacity is not available in literature. Also some preliminary results using the buffer capacity of a freezer in a simple DR strategy (a day/night tariff structure) is presented. Those results are obtained from a simulation using a mathematical model of the freezer.

Fig. 1 Experimental set-up

II. EXPERIMENTAL IDENTIFICATION OF THE ENERGY CONSUMPTION

The dynamic characteristic of a freezer has been measured by monitoring temperature and energy consumption. The measurements consider a number of parameters like filling degree, ambient temperature and setpoint of the freezer itself. Also consumer behaviour is simulated by changing the frequency and duration of freezer-opening. To examine the exact possibilities for DR, the energy consumption of a freezer has to be determined for all possible operating conditions. Fig. 1 shows the experimental set-up for this purpose.

A best available technique (BAT) device (Liebherr GTP3126) is used (energy class A++). The device was put in an acclimatised room to investigate the influence of ambient temperature. The temperature inside the freezer was measured by thermocouples and logged on a 5 second time base. The electric power was also logged with this interval. To simulate consumer behaviour, a PLC was programmed to operate a compressed air cylinder which can open and close the freezer on a regular basis. The command for opening can be given manually or fully automatic during a specified time on specific time intervals.

Measurements have been done for an ambient temperature of 18°C. To quantify the extra losses when the ambient temperature rises, a completely filled freezer was measured in steady state condition on different setpoints (-18°C, -20°C, -22°C, -26°C and -28°C) once with an ambient temperature of 18°C and once with an ambient temperature of 20°C. Note that in steady state condition the energy consumption of an empty freezer will be practically the same as that of a full freezer. This is because in steady state condition the freezer only has to compensate the energy losses, which depend mainly on freezer construction (insulation). Fig. 2 visualizes the results. The upper line represents the energy consumption for an ambient temperature of 20°C, while the lower line visualizes the energy consumption for an ambient temperature of 18°C. It is clear that the freezer consumes more in a room with 20°C. A two degree rise in ambient temperature results in an increase of energy consumption of 6%.

By law [16], products may not be stored warmer than -18°C. A minimum temperature is however not specified. Fig. 2 makes clear that energetically it is not wise to set the setpoint much lower than -18°C. At a setpoint of -28°C, energy consumption rises with 65% (from 165 to 275 kWh on a yearly base). Some sources however mention that certain products should be stored much colder (eg. ‘rich Italian ice cream’ should be stored at -26°C [17]).

Another remarkable finding is the final steady state temperature. This is lower than the original setpoint and depends also on the ambient temperature (higher steady state temperature with the same setpoint but with a higher ambient temperature).

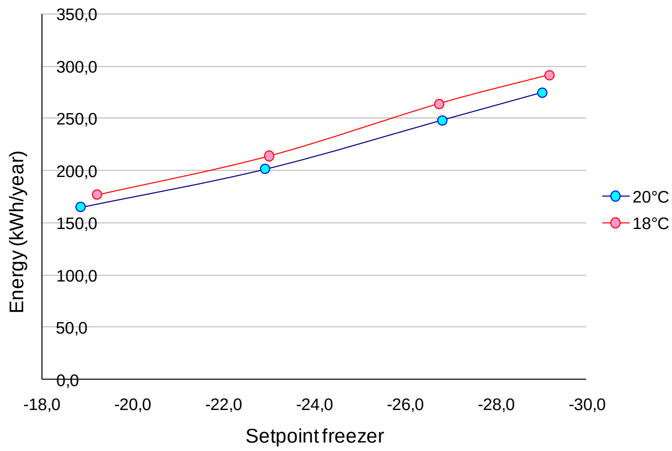

Fig. 2 Influence of the ambient temperature on energy consumption of a freezer

To investigate the capability for DR, the buffer capacity has to be determined. In addition to the measurements of steady state conditions the transitions between two steady state conditions and the time needed to cool or to warm up to a new setpoint have been measured. These times are a key factor for the buffer capacity and depend on the filling degree of the device. Three situations are considered; an empty freezer, a half filled freezer and a fully filled freezer. The freezer is (half) filled with bottles of water, which represents relatively well a normal filling because most products contain a large amount of water.
To model the freezer for these situations, data is needed for setpoint -18°C, setpoint -28°C, cooling and warming. Fig. 3 shows temperature and power for a transition from -18°C to -28°C for a half filled freezer.

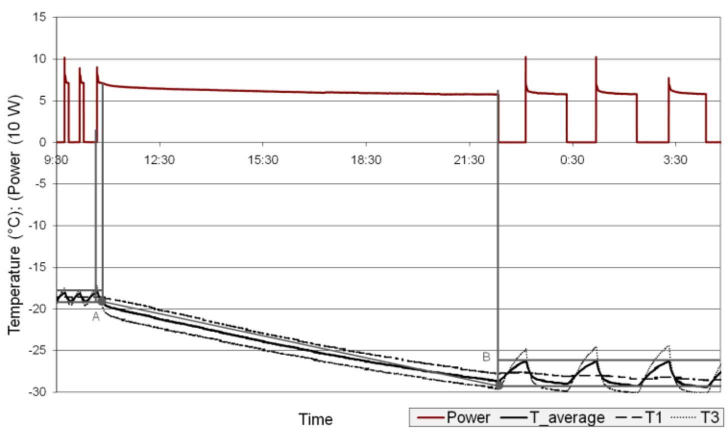

Fig. 3 Transition from -18°C to -28°C: Temperature and power

The upper line represents the power divided by 10. The lower lines represent temperature on the bottom (T1) and on top (T3) of the freezer, and the calculated average between those two temperatures. It is this average temperature that is used to model the freezer temperature.

Table I and Table II summarize the most important parameters for respectively cooling en warming between setpoints -18°C and -28°C. An empty freezer warms and cools rapidly which results in a negligible buffering capacity. A full freezer can postpone its consumption with 30 hours as temperature rises from -28°C to -18°C, but needs 20 hours of power to produce this buffer capacity. The buffer capacity of a half filled freezer is almost half of that of a completely filled one. The filling degree appears to be the most determining parameter for the buffer capacity.

Table I Cooling parameters

	Start T	End T	Δ T	Δ time	°C/hour
empty	-21,2°C	-31,2°C	-10,0 °C	41'	-14,5°C/h
Half filled	-19°C	-29,3°C	-10,3 °C	11h32'	-0,89°C/h
full	-18,9°C	-28,9°C	-10,0 °C	20h48'	-0,48°C/h

Table II Warming parameters

	Start T	End T	Δ T	Δ time	°C/hour
Empty	-27°C	-17,9°C	9,1°C	57'	9,593°C/h
Half filled	-26,3°C	-17,9°C	8,4°C	15h47'	0,532°C/h
Full	- 27,9°C	-18,3°C	9,6°C	30h36'	0,312°C/h

To bring the consumer behaviour into account, all measurements have been repeated while opening the cover a number of times per hour during a certain time. Automation of the system led to a uniform opening pattern for the three different filling degrees and made it relatively simple to investigate different user behaviours.
Fig. 4 shows energy consumption for setpoint -28°C as a function of total opening duration per hour. The different lines represent the different filling degrees. The duration of opening has a significant influence for all these filling degrees. Energy consumption rises from 275 kWh (-28°C, closed) to up to 340 kWh (-28°C, 2 minutes open per hour). For a total opening duration of 1 minute per hour, the energy consumption has also been measured when the freezer opened four times per hour, with a duration of 15 seconds each time. The results make clear that, although the total opening time is the same, the energy consumption is higher when the freezer opens more frequently.

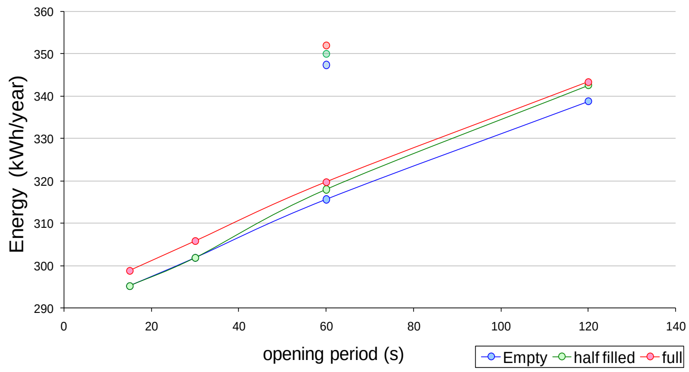

Fig. 4 Effect of consumer behaviour on energy consumption with setpoint -28°C

Not only energy consumption changes with opening duration. The total buffer capacity is also influenced in a negative way. Table III and Table IV compare the buffer capacity for a closed freezer to the buffer capacity with a consumer behaviour equivalent to an opening duration of 1 minute per hour. Table III compares the cooling time and Table IV compares the warming time.

Table III Influence of consumer behaviour on cooling time

	Half filled		Full	
	Δ time cooling	°C/hour	Δ time cooling	°C/hour
closed	11h32'	- 0,89°C/h	20h48'	- 0,48°C/h
1min/h open	13h49'	- 0,74°C/h	24h42'	- 0,41°C/h
Ratio	1,2		1,19	

Table IV Influence of consumer behaviour on warming time

	Half filled		Full	
	Δ time warming	°C/hour	Δ time warming	°C/hour
closed	15h46'	0,532°C/h	30h36'	0,312°C/h
1min/h open	13h41'	0,614°C/h	27h11'	0,351°C/h
Ratio	0,87		0,89	

Opening the freezer during one minute per hour results in a 20% longer cooling time (more energy use) and around 12% shorter warming time (thus less buffer). Note that this user behavior is more severe than mentioned in the Japanese standard[3] where only 12 openings of 10 seconds per day is mentioned [18].

III. Model of the Freezer

From the results of the above experiments a model of the freezer has been constructed in order to simulate different control strategies for DR. The freezer has been modelled with four states: two steady states (-18°C and -28°C) which correspond to the normal operation of the freezer for those setpoints and two transition-states (cooling and warming). In the model, the transition has been linearised, which is justified as Fig. 3 shows (transition between points A en B). The model has two inputs and three outputs. Besides instantaneous temperature and instantaneous power, a third output gives energy consumption on a yearly base. The latter is used to compare different strategies over different time periods.

The first input determines the filling degree. Based on the filling degree, the model selects the correct parameters for the freezer. The other input comes from a control strategy for DR. This control strategy specifies when the freezer should cool deeper to enlarge the buffer capacity (e.g. cheap energy or local energy production available) and when it should avoid to consume energy (e.g. high prizes or national peak consumption). Of course when the maximum allowable temperature is reached, the freezer has to stay in the upper steady state to guarantee food quality. On the other hand there is also a minimum temperature that the freezer can generate, due to safety precautions (avoid freeze burns) and limitations of the cooling device.

An example of power (upper graph) and temperature output from the model can be seen in Fig. 5. The freezer starts in setpoint -18°C when it receives a signal to cool (eg low price signal). The freezer reaches its minimum temperature and stays at setpoint -28°C as long as the signal to cool stays. At a certain moment the freezer receives a signal to avoid energy consumption (e.g. high price signal) and warms up to -18°C.

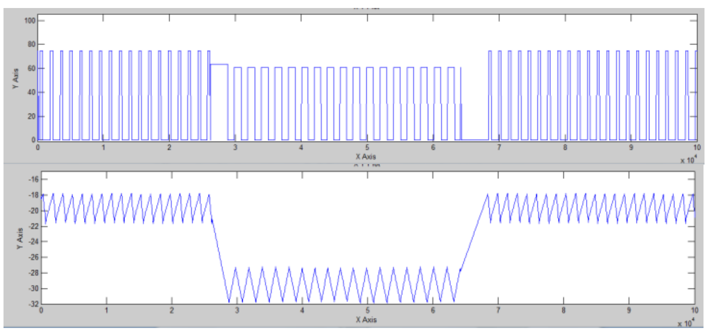

Fig. 5 Power and temperature

A non electrical remark that can be made, is whether the fluctuation in temperature has an impact on food quality. The night wind project [19] has examined the quality of stored food with temperature fluctuations between -18°C en -28°C. The project concluded that, quality decay is negligible and can be offset by the obvious economic benefits, which DR can afford. This allows to fully exploit the buffer capacity without a significant loss of food quality. Note that some big cooling storage houses already apply similar strategies. During the day people have to work in the storage houses, which would be uncomfortable if the cooling groups are blowing cold air in the space. Therefore, the storage house is cooled to -30°C during night-time so that people can work without the cooling groups blowing cold air during daytime [19].

[3] We refer to the Japanese standard (JIS C9607-1999) because user behavior is not yet taken into account for energy labeling in Europe and the US.

IV. THE USE OF THE BUFFER CAPACITY OF THE FREEZER FOR DR

Different control strategies can be simulated using the model. As a case study a strategy has been simulated, to minimise the energy cost based on a double tariff structure (day/night) for a domestic electricity user. The strategy consists in cooling maximally during night time and as little as possible during day time. To that end energy consumption and temperature are continuously analysed to determine whether the buffer capacity is sufficient or not.

Fig. 6 shows power and temperature for a completely filled freezer. Note the time base of 105 seconds. So one unit is slightly more than one day. The freezer has to cool during the whole night (9 hours from 10 pm to 7 am) to reach a temperature of around -23°C. The steady state of -28°C cannot be reached. Due to the created buffer the freezer only needs to cool a very short period during the day. This can be seen in the short peaks in the energy consumption at the end of the day.

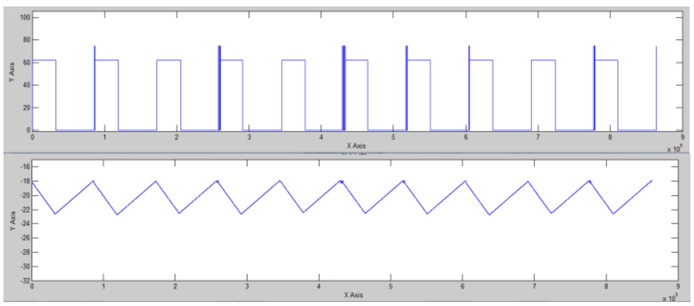

Fig. 6 Power and temperature over 10 days with day/night strategy on a full freezer.

For a half filled and completely filled freezer, the energy consumption and cost on a yearly base are also simulated with the day/night strategy. As already mentioned, an empty freezer does not have a significant buffer capacity so that it is not useful for DR. Table V summarizes the results for energy consumption. Almost all energy can be shifted to the night but total energy consumption increases with approximately 20%. So the difference between day and night prices has to be significant for any economical gain.

Table V Energy consumption with and without strategy

Consumption (kWh/year)	Empty		Full	
	day	night	day	night
Without strategy	106,3	63,8	106,4	63,9
With strategy	97,4	74,4	2,1	202,2
Difference (kWh)	-8,9	10,6	-104,3	138,3
Difference (%)	-8,4	16,6	-98	216,6

Table VI summarizes the financial results for different energy suppliers in Flanders (Belgium). Depending on the energy supplier, the economical gain varies between 2 and 4 € per year for this freezer or between 7,5 and 16%. Note that switching from energy supplier can also deliver an economical gain of 4,5€.

Although there can be some minor financial gains, this strategy is not useful from an energetic point of view. Moreover, the financial gain will probably not suffice to compensate for the extra costs to implement the necessary intelligence. However, the principle will become energetically useful if the buffer capacity is used to allow more renewables to the grid without having to implement more balancing power (ancillary service) from fossil energy plants and/or without having to reinforce the distribution grid.

Table VI Energy cost per year

Energy cost (€)		empty	full
Cost single tariff	Supplier 1	28,10	28,13
	Supplier 2	30,16	30,20
	Supplier 3	32,41	32,45
Cost double tariff	Supplier 1	25,46	25,50
	Supplier 2	27,19	27,22
	Supplier 3	29,88	29,91
Cost double tariff with strategy	Supplier 1	25,06	21,37
	Supplier 2	26,93	25,08
	Supplier 3	29,59	27,66

For Belgium all domestic freezers can represent a balancing power of +/-300 MW that can be switched on or off during long periods (20 to 30 hours). Taking the cooling installations in the distribution and the industrial sector into account, the balancing power is even several times higher. The flexibility of a freezer can be translated in an economical value (flexibility sold as ancillary service), increasing the financial gain for the owner of the freezer. On the other hand, the distribution grid operator (DGO) can impose a maximum permissible power injected in the grid, resulting in a maximum allowed installed power of the local (renewable) energy source. In Belgium, for large (Pnom >10kW) PV-installations, it appears that about one third of the total produced energy is injected into the grid [20]. When the consumer has a buffer capacity of freezers and uses them for DR, the maximum allowed installed power of the distributed source can be higher, whereas the injected power does not increase and the permissible power injected in the grid will not be trespassed. In this case DR is a boost for the 20/20/20 measure of the EU. It allows a higher installed power of RES given the constraints (limits) of the grid.

V. CONCLUSION

The dynamic load characteristic of a freezer has been measured and quantitative results of its buffer capacity have been presented and discussed. From those results a mathematical model of the freezer has been constructed in order to simulate different control strategies for DR. The measurements have been done for one specific type of domestic freezer, but the established working method is equally applicable to any other freezer and easily extendable to other types of controllable loads. Thus the results and conclusions of this work are generic, and not limited to the measured freezer.

A freezer has a significant buffer capacity (up to 30h when it is completely filled and operates at -28°C), but financial gains for domestic purposes are, as expected, not satisfying in the current double tariff structure. However using the buffer capacity of a freezer can be useful to allow more renewable sources to the grid. The freezer can be used for balancing purposes and the injected power in the grid can be reduced so that a higher installed power of the local source can be allowed.

Exploiting a freezer on a lower setpoint increases energy consumption (up to 65% when continuously operating at -28°C). So attention has to be paid to total energy consumption compared to buffer capacity.

The extra consumption can though be limited to around 20% for a time buffering of 15 hours. This is acceptable knowing that with current best available storage techniques, losses amount for minimum 25%. Using the natural storage capacity of a freezer, the installation of some extra storage capacity can be avoided, minimizing the total cost for the necessary infrastructure to implement renewable sources. The cost of the necessary intelligence of the freezer will be negligible in comparison to the cost of the avoided extra storage capacity.

Buffer capacity depends mainly on the construction (insulation) of the freezer and of the filling degree. An empty freezer has practically no buffer capacity and consumes almost as much as a full freezer. So, besides the energy class of the freezer, people should have to spend (more) attention to the size of freezer they actually need.

Further research will be done using the demonstrated flexibility to allow more renewable sources like PV on the grid.

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