WP 3.5
Application of Smart Energy Networks

Potential flexibility of reefers

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Photo: Colourbox

Contents

1 Introduction

Smart energy networks are intelligent and flexible solutions which combine flexible energy consumption, local generation of (renewable) energy and energy storage on different levels. In any smart energy network, the presence of flexible energy consumption is crucial. This document elaborates on one of the new sources of flexibility which is briefly discussed in chapter 4 of [1]: refrigerated containers, commonly abbreviated as "*reefers*".

First a short introduction is given, introducing reefers together with some key aspects. In chapter 2 the outcomes of some simulations, related to identifying the potential flexibility in reefers, are discussed. In order to verify the outcomes of the calculations given in chapter 2, an experiment was conducted of which the results are discussed in chapter 3. These results are compared with the ones discussed in chapter 2. To conclude we summarize our findings and state some conclusions of our work done on this subject.

1.1 Key aspects of reefers

A lot of the maritime transport of refrigerated goods happens in refrigerated containers, often called "reefers" (shown in Figure 1). Reefers need electric power for cooling and freezing their cargo, some key figures of a conventional reefer are:

- Peak power: 10 – 15 kW
- Temperature Range: -30°C – 30°C
- Average energy consumption: 3 – 4 kWh
- Insulation: 0.4 – 0.7 W/m^{2}K

Figure 1: Reefer

Looking at the global picture, for example in the Antwerp harbour, these figures become very large as they have a yearly throughput of 8,664,243 twenty feet equivalent units (TEU) [2]. The majority of the containers are 40 ft so dividing by 1.8 results in a throughput of 4.813.468 containers in the Antwerp harbour in 2011. It has a total of 5.000 connection points, meaning that 5.000 reefers can be connected to the grid simultaneously. Because of the huge amount of reefers available in the harbours and their substantial energy consumption, we analyzed the theoretical and practial flexibility of these reefers, a summary of this analysis is given in the remainder of this report.

2 Reefer Flexibility: Theory

2.1 Flexibility in power

Taking the figures given in section 1.1 we can make some rough estimates of the power flexibility available in the reefers at the Antwerp harbour. In 2012 a total of 480.000 reefer TEU were handled, dividing by 1.8 results in 266.666 reefers on a yearly base [3]. The average connection time at the terminal is 3 to 4 days, so in total they remain in the harbour for 1.066.664 days which comes down to 2900 reefers/day present in the Antwerp harbour. Taking into account that 50% are operating in freezing mode, this is important because it is too critical to vary the temperature in cooling mode because the cargo requires a very specific temperature, a total of 1450 reefers are available counting up to 14.5 to 21.7 MW of flexibility. This leads to the comparison shown in Figure 1 where the power flexibility of reefers is compared to the power flexibility from the companies identified in [1]. It clearly shows that reefers have a huge potential in power flexibility.

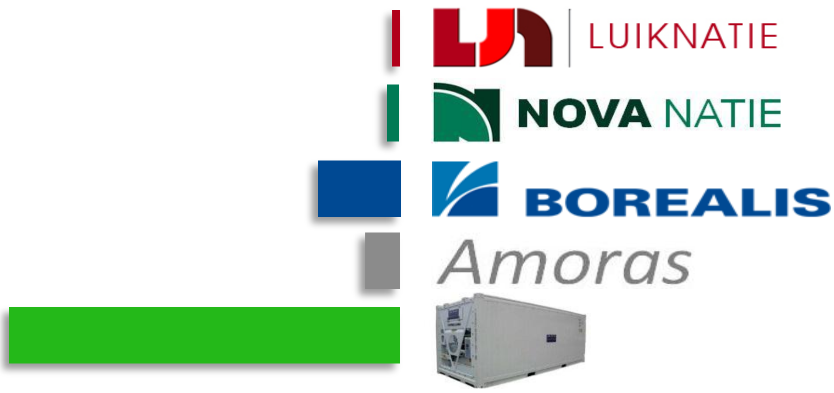

Figure 2: Comparison of the flexibility expressed in power

2.2 Flexibility in Time

To check if the power flexibility is useful for enabling active demand response, the time window in which this power can be shifted has to be identified. A simplified model of a reefer was implemented to get an idea of the time shift potential. The simulations showed that the average temperature in a well insulated reefer increases with 1ºC per 5 hours in an outside temperature of 20°C when the reefer is switched off. Under the assumption that a temperature window of 5ºC (e.g. -19 ... -24ºC) is acceptable, this means that it is possible to maintain the temperature for 24 hours without power. To check these numbers, datasets of temperature measurements together with the related power consumption are needed. We were unable to obtain these datasets and therefore it was decided to rent a 40 feet reefer and execute the measurements ourselfs. The next chapter discussed the test setup which was built and the results emerging from the experiment.

3 Reefer Flexibility: Practice

In order to check the flexibility identified in the theoretical calculations, we rented a reefer and loaded it with IBC's (filled with water), together with the cargo 12 temperature sensors were put in place in order to log the temperature throughout the reefer.

3.1 Test setup: equipment

The test setup consisted of the following equipment:

1. One 40 ft reefer (12.19m x 2.44m x 2.89m)
2. 24 IBC containers , capacity = 1000l (1m x 1.2m x 1.17m)
3. Fluke 1745 Power Quality Logger Memobox
4. 2 Datatakers DT80 fitted with 8 PT-100 temperature sensors
5. 4 Tinytag Plus temperature loggers
6. 1 Dell Latitude E6410 laptop

The 24 IBC containers are filled with water (≈ 800l each, 19200l in total) and placed in the reefer according to the scheme depicted in Figure 3. As shown the container is loaded in 2 layers:

- *Bottom layer:* 18 IBC containers in 2 rows of 9 each
- *Top layer:* 6 IBC containers placed on top, on one side to be able to reach the measurement sensors during the experiment (in case of failure etc).

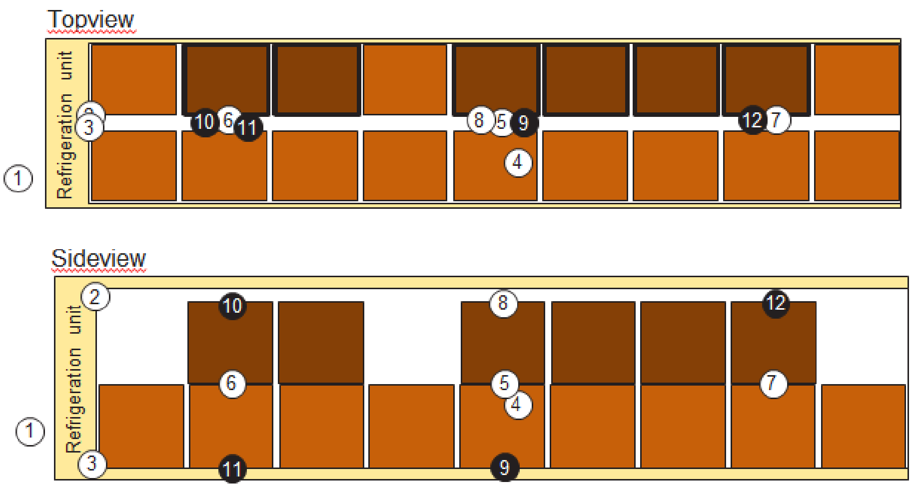

Figure 3: Load scheme reefer

The numbers in Figure 3 show the location of the different temperature sensors, the white ones are the PT-100 temperature sensors connected to the datatakers, the black ones are the standalone Tinytag Plus loggers. Sensor 4 is inserted into the cargo to enable logging of the cargo temperature.

3.2 Test setup: Goal & Methodology

The goal of the experiment is twofold, we want to obtain the following information:

- Switching behaviour of an individual reefer (ON/OFF behaviour)

- The influence of the temperature boundaries on the switching behaviour of the reefer e.g. if the setpoint of a reefer is changed, how long will the consumption be shifted. This will give an insight on the reefer's flexibility in terms of time.

The power measurements together with the PT-100 temperature measurements were logged every minute whereas the Tinytag Plus loggers logged their values every 2 minutes due to memory constraints. In order to reach the goal, the following test cycle was applied in the experiment:

1. Cool/freeze the cargo untill it reaches the setpoint of -22**°C**
2. Change the setpoint to -17 °C and wait untill it is reached
3. Change the setpoint to -22 °C and wait untill it is reached
4. Disconnect the reefer from the grid to warm up the cargo to the outside temperature

3.3 Experiment: Execution & Results

The following timeline shows the real execution of the experiment. Informative events during the experiment are given in green whereas events influencing the experiment are shown in red:

1. **09/01/2014 16:00**
   a. Start experiment, setpoint reefer -22°C
2. **10/01/2014 16:10 to 14/01/2014 15:18**
   a. No temperature readings sensor 1 t.em. 8 cause: faulty measurement equipment
3. **17/01/2014 13:22 to 21/01/2014 11u33**
   a. See 2a
4. **21/01/2014 11:33**
   a. Agilent measurement device (T1 .. T8) replaced by datatakers
5. **25/01/2014 00:00 to 27/01/2014 12u56**
   a. No power logging, cause: faulty measurement equipment
6. **27/01/2014 14:50**
   a. Setpoint reefer changed from -22°C to -17°C
7. **28/01/2014 15:50 to 29/01/2014 7:00**
   a. reefer + measurement equipment plugged out
8. 1/02/2014 00:22
   a. Tinytags (T9 t.e.m. T12) stopped logging (memory full)
9. **05/02/2014 11:00**
   a. Setpoint reefer changed from -17°C to -22°C
10. **7/02/2014 13:30 to 7/02/2014 13:40**
    a. Opening doors of reefer for 10 minutes
11. **7/02/2014 16:00**
    a. Reefer unplugged, warming up to ambient temperature
12. **13/02/2014 10u37**
    a. End of experiment

As seen in the list above, the total duration of the experiment was 5 weeks. In the beginning there were some problems due to downtime of the installed measurement equipment, this lead to some gaps in the logged datasets. However after 10 days the faulty equipment was replaced and from 21/01/2014 all logging was working as it should. In Figure 4 the complete dataset is visualized and the important events are pointed out.

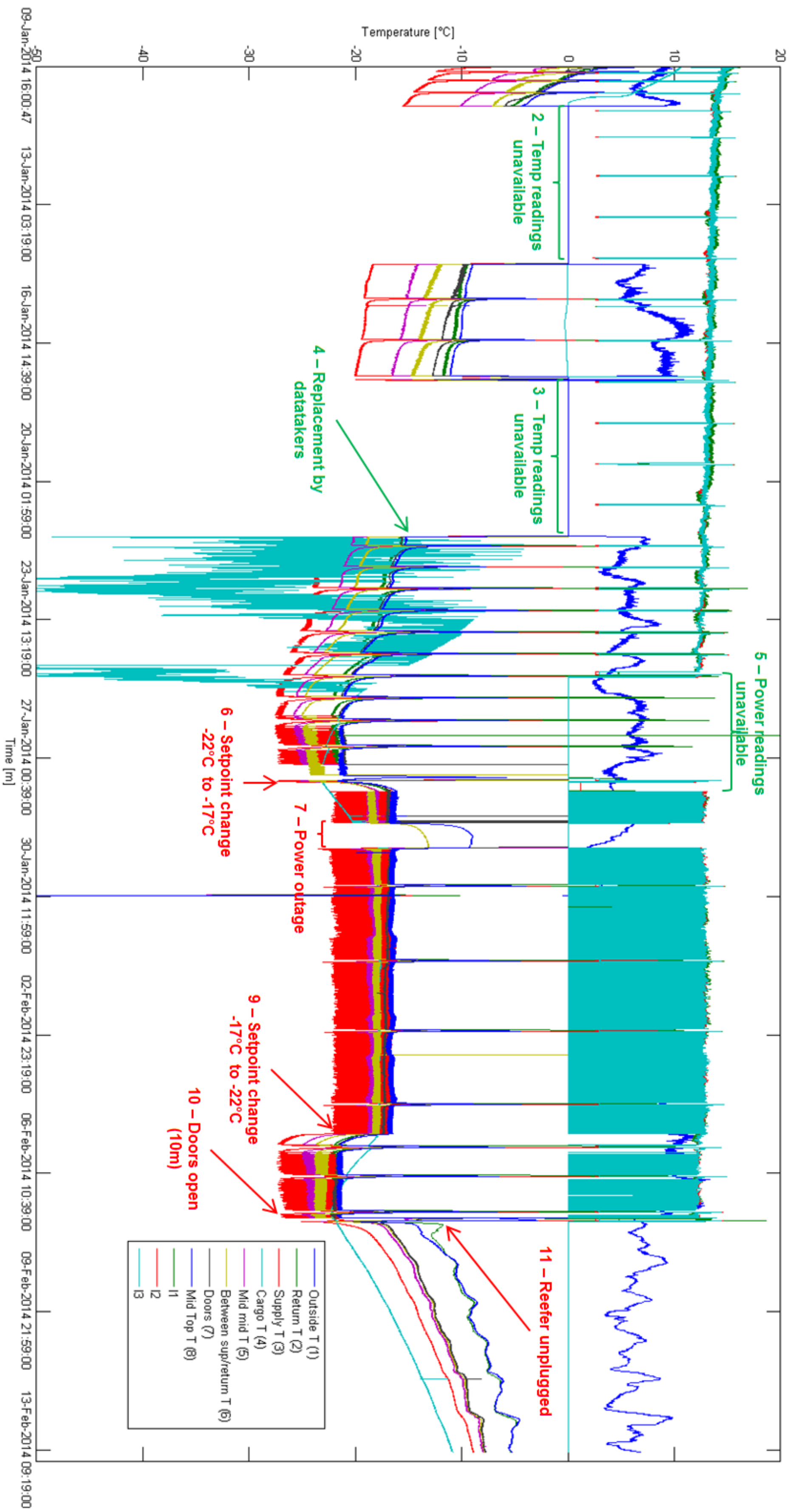

Figure 4: Temperature and power readings reefer experiment

3.3.1 Temperature window effect

One of the most important goals of the experiment is identifying how long the energy consumption of a reefer can be delayed, making use of the technology available in a conventional reefer. This implies that, in order to delay the energy consumption, we can only rely on changing the freezing setpoint of the reefer. In this experiment we changed the setpoint to see what the effect was on the temperature and thus flexibility. Zooming in on event 6 when the setpoint of the reefer was changed from -22°C to -17°C (ΔT = 5°C), the behavior shown in Figure 5 is observed. On the x-axis it is seen that that the reefer is switched off from 15:10h until 20:50h, resulting in a flexibility window of 5:40h. This resulted in the following temperature variations:

- Return temperature of the air in the reefer: from -21.5°C to -17.5°C (ΔT = 4°C)
- Cargo temperature: from -23.1°C to -22.5°C (ΔT = 0.6°C),

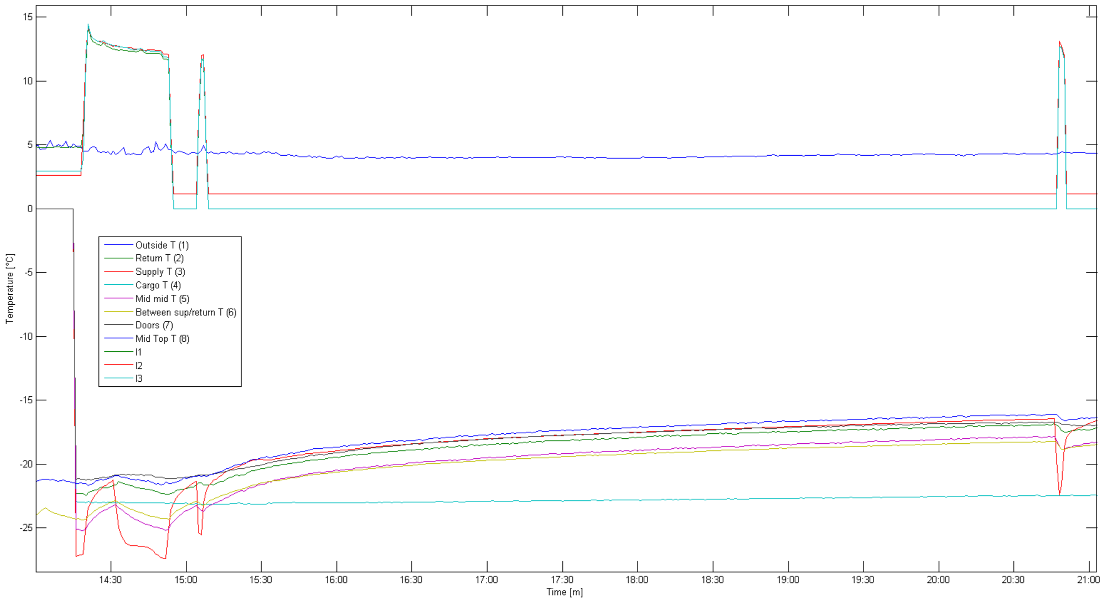

Figure 5: Behavior when setpoint is changed from -22°C to -17°C

Comparing these results with the ones from the theoretical calculations described in section 2.2 we see that the real flexibility value (6h) is much lower than the one that was calculated (24h), aproximately 4 times less. Two major reasons exist to explain these differences:

- Heat transfer from cargo to air was not as good as modelled in the simulations
- The insulation of the reefer was not as good as modelled in the simulations

At times the reefer is not cooling, the air temperature in the reefer only depends on the heat transfer from the cargo to the inside air and the heat transfer from the environment to the inside temperature. Both phenomena happen with different time constants, therefore at first the air temperature rises quickly due to the influence of the environment but after the initial rise the heat transfer from the cargo to the air takes over which leads to a much slower rise of the air temperature in the reefer.

3.3.2 U-value reefer

Looking at the measurements emerging from our experiment it is important to question the reefer's U-value. The insulation value of reefers is commonly expressed in this U-value. It is expressed in W/°C. For example if the U-value of a container is 40 W/°C while its interior temperature is 0 °C and ambient temperature is 30°C then the heat ingress Q_{ext} is 40 x (30 – 0) = 1200 W. The lower the U-value the smaller Q_{ext} and hence the better the insulation.

If we zoom in at the last 5 days of the experiment where the cargo in the reefer was warming up to the ambient temperature, we see the following measurements:

- 07/02/2014 16:00 –> T_{cargo} = -21.7°C
- 13/02/2014 08:00 –>T_{cargo} = -11.0°C

Taking into account that the cargo consisted of 19000kg of ice and average $T_{ambient}$ = 6.2°C, following calculation holds:

- The energy transferred from the cargo to the air
  - $E = \rho_{ice} * m_{ice} * \Delta T$ = 0.001163 kWh/kg.°C * 19000 kg * (21.7°C – 11.0°C) = 236.44 kWh
- The U-value of the reefer
  - $U = E / (time * (T_{inside} - T_{amb}))$ = 236.44 kWh / (136h * (16°C+6.2°C) = 0.078 kWh/h.°C

Comparing this value with the 0.4 W/m^2.°C from section 1.1 we see that, taking a reefer surface of $100m^2$, the measured U-value is double as high as the theoretical one. This is one explanation for the time flexibility being 4 times less in our experiment than it was in the theoretical calculations. The major reason for this is most probably the degrading of the insulation of the reefer over the years as the reefer in the experiment was about 13 years old. In other experiments described in [5],the U-value of a 2 year old reefer was compared to a 4 year old reefer where the insulation of the oldest reefer has degraded 15% in comparison with the fairly new reefer. This implies that the usable flexibility in reefers is dependant of the U-value of the reefer and therefore also dependant on the age of the reefer.

4 Summary & conclusions

The initial simulations revealed that there is a significant amount of energy flexibility available in reefers clustered in the harbour. In power this comes down to 14.5 – 21.7 MW in the harbour of Antwerp. The average connection time of a reefer at the terminal is 3 to 4 days which is sufficient to exploit the flexibility by applying active demand response. The simulations also showed that a temperature window of 5°C on the air inside the reefer could result in a shift in demand for 24h. In order to check these figures, temperature datasets together with power datasets were sought to be able to check the real behavior of an individual reefer. Because multiple actors are involved: the company leasing the reefer has access to the temperature readings and the terminal operator has access to consumption profiles of the reefers etc. we were unable to obtain the necessary datasets. For this reason, we conducted an experiment to model the behavior of a single reefer. In this experiment the flexibility in which the demand of the reefer could be delayed in time was 4 times less (6h) than the one calculated in the simulations (24h), which is probably due to the degrading of the insulation in the reefer. Therefore we can conclude that the overall flexibility in reefers will be significantly lower than the 24h calculated in the simulations because of the lifetime of reefers which is > 10 years. However, in this worst case of a 6h flexibility together with an air temperature window of 5°C this is still sufficient to exploit the flexibility on the day-ahead market or for local balancing purposes with regards to wind and/or solar production.

In order to really exploit the available flexibility some issues need to be tackled. Every reefer should be fitted with a bi-directional communication system to enable remote control of the setpoint temperature. Currently a lot of new reefers are already fitted with such a system but the conversion will only be conducted gradually. Another big challenge to really start using the available flexibility is convincing all the stakeholders in the total transportation chain of the need to do so. For example the terminal operator wants to use the demand side flexibility to lower its energy bill, however this will have an impact on the cargo temperature so the owner of the cargo needs to agree and needs to have an incentive to do so. On the other hand there is also the leasing company of the reefer which needs to agree because the switching behavior in an active demand response system can have negative impact on the lifetime of the compressor etc. It goes without saying that all stakeholders in the transportation chain need to agree and need to be fairly incentivized for the flexibility offered. Apart from these technical and economic boundaries, it should be noted that the boundaries of the temperature window are decided by the owner of the cargo. It is of utmost importance that all rules with regards to food regulations are met at all times. Within these rules the carrier can offer a lower price for transportation if a specific temperature window is offered by the cargo owner.

5 References

[1] E-harbours deliverable 3.5, *"Application of Smart Energy Networks – part **I** & part **II**: Summary results show case Port of Antwerp"*

[2] *"2011 in figures"*, available at http://www.portofantwerp.com/en/2011-figures

[3] http://www.portofantwerp.com/perishables/

[4] "*ISO 10368:2006 – Freight thermal containers – Remote condition monitoring* ", available at http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=36595

[5] Optimizing shipment of lily bulbs in 40 ft reefer containers, available at bulbs in 40 ft reefer containers, available at http://edepot.wur.nl/240296