Final report

1. Project details

Project title	eTRU – Energy efficient and reliable control systems and power conversion chains for plug-in battery electric transport refrigeration units applied in semi-trailers.
File no.	64019-0072
Name of the funding scheme	EUDP
Project managing company / institution	Bitzer Electronics A/S
CVR number (central business register)	DK 21 34 00 06
Project partners	Syddansk Universitet
Submission date	10 February 2023

2. Summary

Describe the objectives of the project, the obtained results and how they will be utilized in the future.

The short description should be in two versions:

- *English version*

English:

The purpose of the eTRU project is to develop and demonstrate an energy efficient and reliable battery powered transport refrigeration unit for tractor trailers. Using electricity from a battery will eliminate particle and CO2 emissions from the diesel generator and help lower the noise level. The project is funded in BITZER Electronics A/S many years of experience within development and production of electronic solutions for refrigerated intermodal reefer containers and SDU extensive knowledge of power electronics and batteries.

A frequency converter suitable for running from a DC source and driving a compressor with permanent magnet motor has been developed along with a control unit that is able to control all the components of the system. A compact refrigeration system has been developed to free up space for a large integrated battery pack. The energy efficiency of the solution has been compared with traditional diesel driven units, and significant savings were demonstrated. BITZER Electronics A/S expects that based on these results it will be possible to find a partner that will produce green and efficient trailer refrigeration units, using our technology and unique knowledge gained through this project.

- *Danish version*

Dansk:
Formålet med eTRU projektet er at udvikle og demonstrere et energi-effektivt og pålideligt batteri drevet køleanlæg til en lastbil køletrailer. Batteri drift giver mulighed for at fjerne CO2 og partikeludledningen fra dieselgeneratoren og sænke støjniveauet. Projektet er baseret på BITZER Electronics A/S mangeårige erfaring med udvikling og produktion af elektroniske løsninger til energi-effektive kølecontainere og på viden om effekt elektronik og batterier ved SDU.

Der er I projektet udviklet en frekvensomformer der kører på DC fra en batteripakke til at drive kompressoren i køleanlægget og en styreenhed med en SW der er i stand til at styre køleanlæggets mange komponenter. Der er udviklet et kompakt køleanlæg for at give plads til en stor integreret batteripakke. Energieffektiviteten er blevet sammenlignet med konkurrenternes og der er påvist en væsentlig forbedring.
På baggrund af disse resultater forventer BITZER Electronics A/S at finde en partner der vil bygge og sælge grønne, energieffektive trailerkøleenheder med vores styring og effekt elektronik, baseret på vores unikke viden der er oparbejdet gennem dette projekt.

Project objectives

- *What was the objective of the project?*

The project objective was to develop and demonstrate a fully electric, battery driven refrigeration system for tractor trailers used in road transport of chilled and frozen goods. The goal was to make a product that can replace most of the existing diesel driven units currently used, without significantly changing the weight, form, or function of the reefer trailer. To achieve this, it was necessary to increase the refrigeration system efficiency significantly and reduce its physical size, compared to existing solutions.

- *Which energy technology has been developed and demonstrated?*

In the project a compact refrigeration system has been shown to be as powerful as the one it replaces while also being more energy efficient. This important to demonstrate because the business we are operating in is quite conservative and potential partners needs to see a proof of concept before investing. The feasibility of tightly integrating a battery pack and a DC driven refrigeration system using advanced controls was also demonstrated, and this technology enables a more accurately controlled temperature in the cargo hold, which improves product quality and reduce the risk of food waste.

3. Project implementation

- *How did the project evolve?*

The project evolved according to the milestone plan in 2019 and beginning of 2020 where the initial project activities including usage pattern was investigated and the system design was developed, both on overall concept level and on the power electronics. The development of the inverter which was done in-house followed the plan, where the battery topology and battery design was done with the help of external partners introduced some delays. With respect to work package 2 and work package 3, the milestones where met only with some delay on the battery deliveries. Combined with the integration part of the mechanical and electrical parts into the complete units, delayed the construction of the road test units, and subsequently the road tests.

- *Describe the risks associated with conducting the project.*

The project was associated with multiple risks both technological risk and commercial risks, where the main commercial risk for BITZER Electronics is related to the manufacturing of the complete refrigeration units, which is the projects deliverables. This should be done by partnering up with a manufacturing partner which also have the possibility to provide service when in operation on the road by the transport company. With respect to the green transition the market is more ready for a fully battery driven solution today, then when we started the project, which is good.

The most prominent technological risk was that it would not be possible to make a refrigeration unit with the required range of operating hours and total cost of ownership.

- *Did the project implementation develop as foreseen and according to milestones agreed upon?*

Yes, the project implementation developed as foreseen in the milestone plan and all agreed objectives were met by the project.

- *Did the project experience problems not expected?*

Covid-19 made it difficult to collaborate on practical tasks and sourcing problems in the time critical phase of integration and where the road test units were built has been very challenging. The low readiness level of some of the components used also required some more adaptions then anticipated at the beginning of then project.

4. Project results

- *Was the original objective of the project obtained? If not, explain which obstacles that caused it and which changes that were made to project plan to mitigate the obstacles.*

The original project objective was not met. As the project ended with the road test samples build by us, and not with commercial sellable systems built by a system builder. However, the technical results of the project have all been met, a battery driven refrigeration system have been constructed, which is a one piece unit, that can be exchanged with an existing diesel driven unit, just closing off the fuel lines. Battery is fully integrated into the frame. The energy performance is as good as expected. The road tests have lead to adaptions of software functionality to ease the operation for the truck driver. Our road test partner is very satisfied with the performance of the units.

- *Describe the obtained technological results. Did the project produce results not expected?*

In the project refrigeration technologies that we knew would improve energy efficiency were utilized together to significantly increase the energy efficiency of the refrigeration system, especially in part load. A non-traditional refrigeration system topology for transport refrigeration were used to significantly reduce the size and complexity of the refrigeration system. This required a new control paradigm that were developed and demonstrated to be both robust and efficient. The technological results are described in further details in the following four sections:

- *1. Concept verification section* - describes the results and activities done to prove the system concept and design

- *2. System controller* – briefly describes the results related to the system controller development, and airflow simulations for energy optimisation
- *3. Power topology* – describes the results and finding within the field of power electronics and the battery pack integration
- *4. Prototyping and operational tests* – describes the outcome of the environment and operational tests

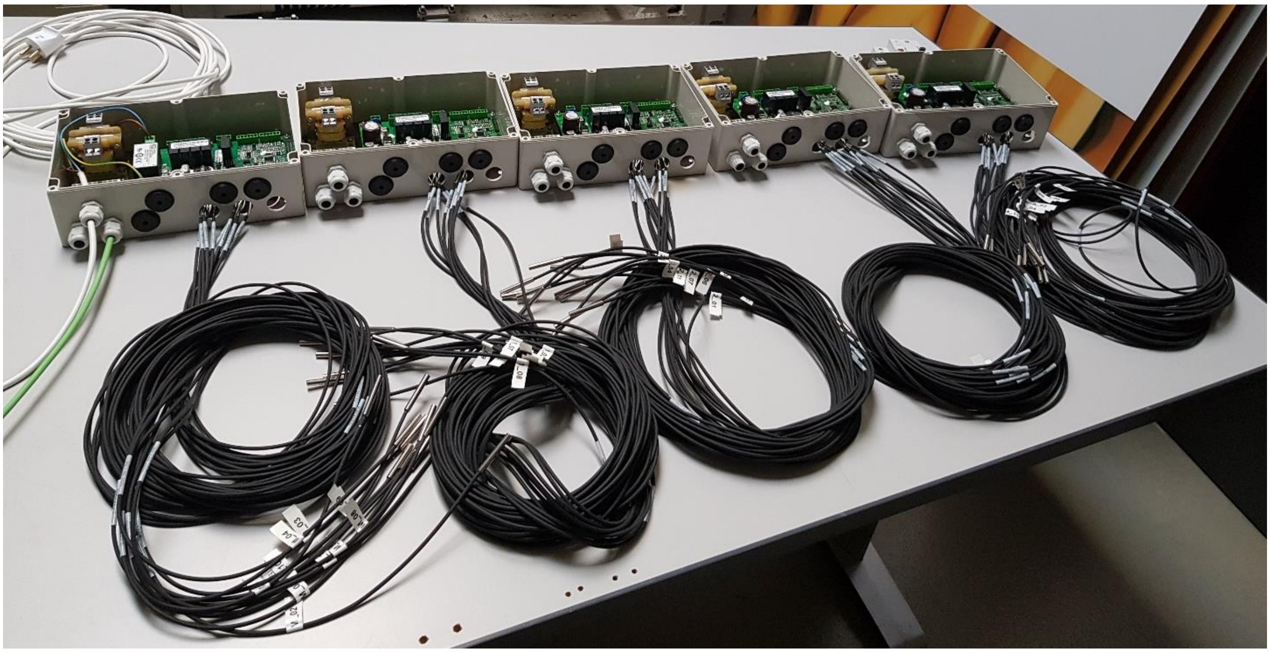
4.1 Concept verification

4.1.1 Test laboratory

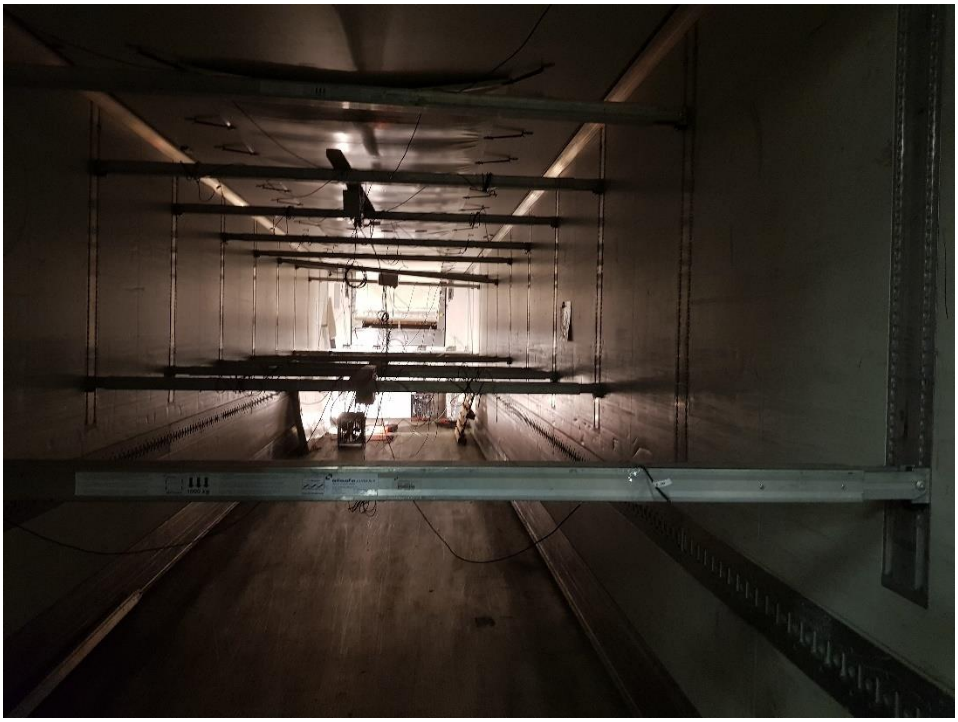
To be able to carry out realistic testing and comparison of the developed refrigeration units it was decided to build a test setup around a full-size trailer equipped with a refrigeration unit. Therefore, a trailer with a refrigeration unit suitable for conversion to battery electric was purchased and moved to the test location.

A test facility was built to be able to reliably simulate a fixed ambient temperature around the whole trailer, enabling accurate testing of refrigeration unit performance. The setup consists of an enclosure that surrounds the unit with automatic temperature control to keep a fixed air temperature and the higher ambient temperature around the trailer is simulated using computer-controlled radiators inside the trailer. These are programmed to compensate for the difference in temperature outside the trailer and the desired simulated temperature. This gives the ability to test the entire system at temperatures higher than what was present during the winter months.

Test platform in front of trailer.



Temperature measurement equipment used to measure air temperature distribution in the trailer. This was used to ensure proper temperature distribution during optimization of the airflow.

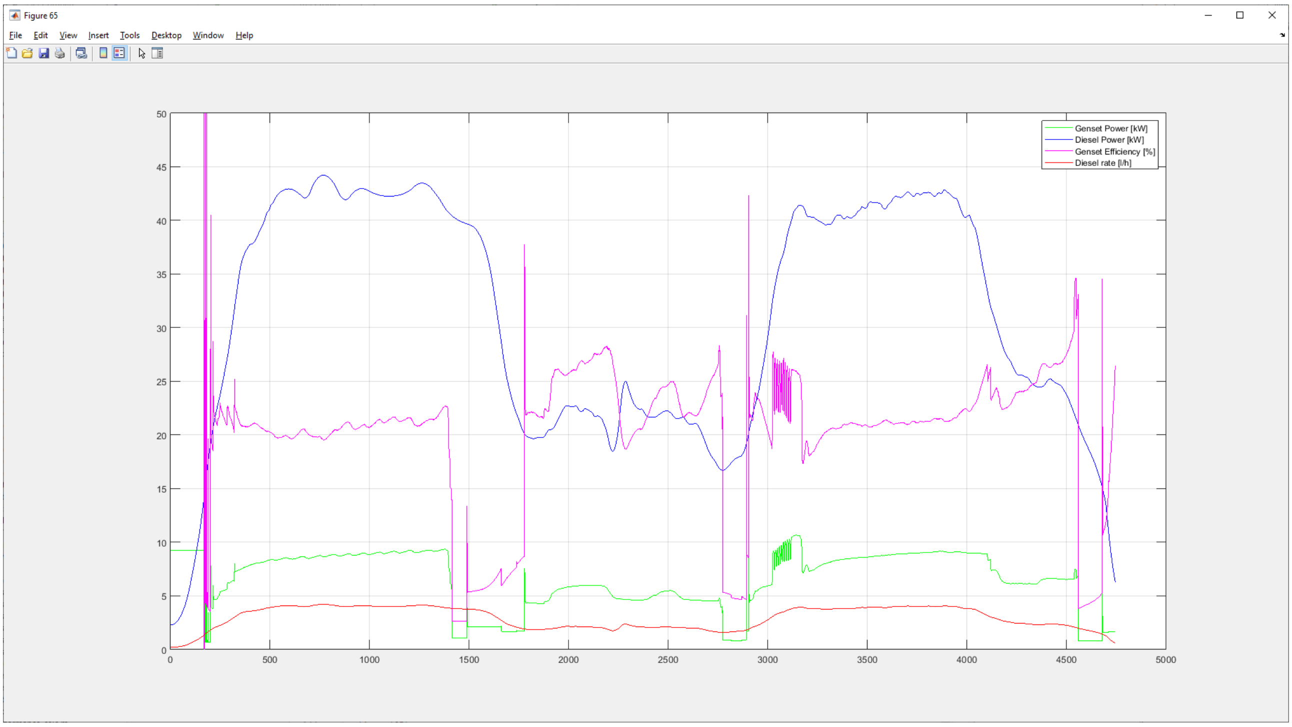


Sensors mounted inside the trailer.

4.1.2 Performance measurement of diesel unit

A semi-trailer with a Vector 1550 was procured and equipped with extra sensors to enable accurate measurement of the systems performance.

Initial test setup on the diesel driven trailer with extra pressure and temperature sensors mounted.



The figure above shows the diesel consumption, the calculated power in the used diesel, genset electrical power and the calculated efficiency of the genset, from diesel to electricity.

In the best-case scenario where the refrigeration compressor is running, and the electrical power provided by the engine is used for refrigeration. In this scenario the efficiency of the diesel genset is between 20% and 30%.

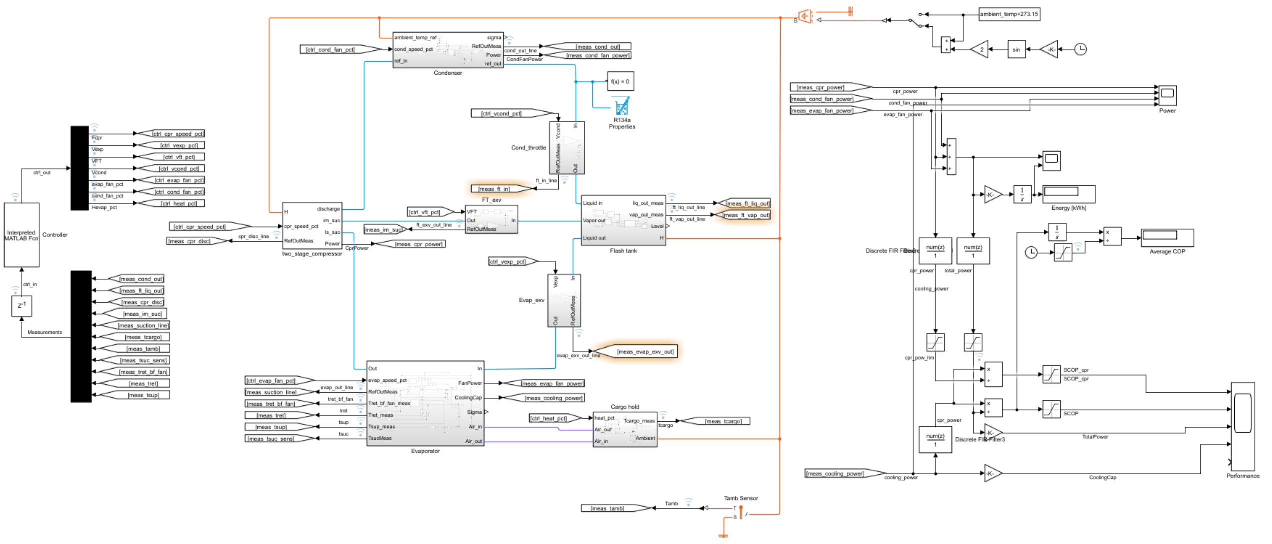
When the refrigeration requirement is low, and the compressor must be stopped to keep temperature over the set-point the efficiency drops to only 5% because only the evaporator fans are running, and these consume much less power than the genset can provide.

This means that 70% to 95% of the energy contained in the diesel is lost and rejected as heat.

The refrigeration system of the Vector 1550 unit was tested for efficiency in shore power mode where the power was supplied by the grid instead of the generator and it was found that the COP of the system was in the range of 0.9 to 1.5, with the best COP in frozen mode.

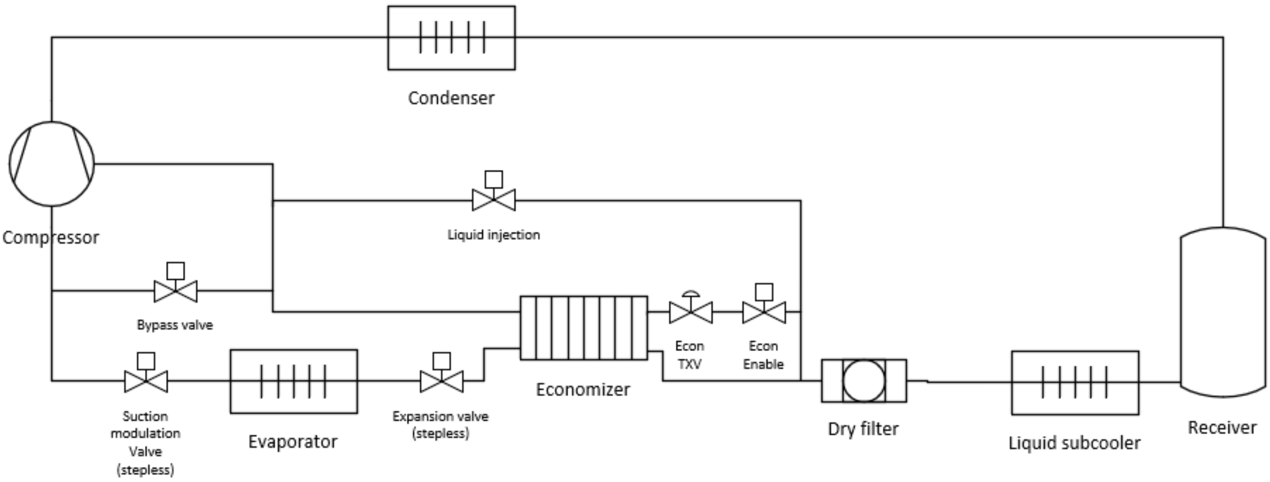
4.1.3 Refrigeration system design

For the initial investigation of possible solutions, a simulation model of the refrigeration system was created, and this was used to experiment with different options, without having to build many different systems.



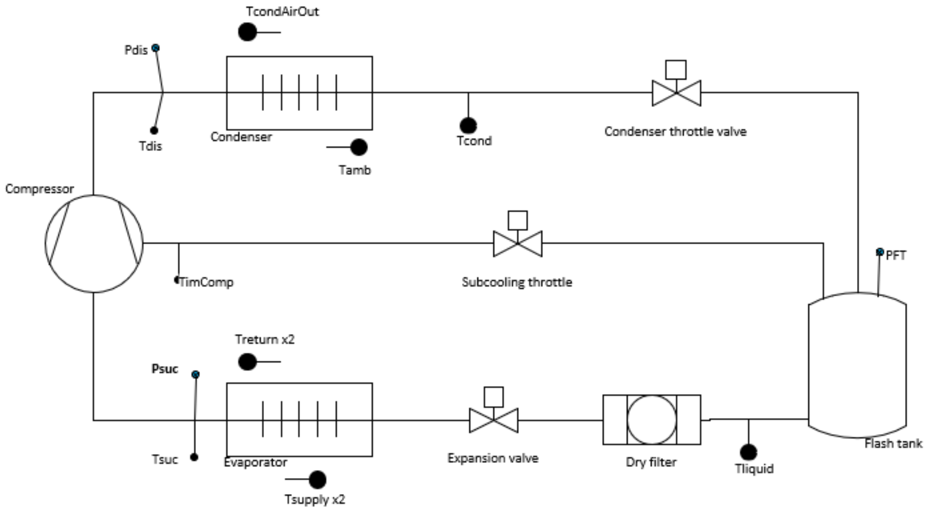
Refrigeration system model used for initial prototyping.

Using this model, it was found that being able to variably control the speed of compressor and the fans that push air over the evaporator and condenser would be required to reach a good efficiency. At the same time the refrigeration system was simplified to create more space for the battery and lower the complexity and cost of this part of the unit.



Original refrigeration system of the Vector 1550

The original refrigeration system was complicated because capacity regulation was done using valves instead of adjusting the speed of the compressor. This type of capacity regulation is inefficient and therefore it was needed to redesign the refrigeration system.



Refrigeration system diagram for eTRU

The eTRU refrigeration system was built with fewer components but because the compressor can be speed controlled the range of capacities it can provide is larger than that of the original refrigeration system.

The first iteration of the mockup prototype is shown on the picture to the right. It was constructed using variable speed fans with efficient permanent magnet motors, and the original compressor from the diesel-driven refrigeration unit.

It was however quickly discovered that his compressor was unable to run at low speeds, because it lost lubrication on the scroll-set that would have destroyed the compressor over time. A replacement compressor that was more efficient and had a larger dynamic speed range was therefore purchased and mounted on the unit instead. This gave a significant increase in system efficiency.

To summarize the main changes for the refrigeration system were:

- The compressor was replaced with a variable speed type with an efficient permanent magnet motor.
- The economizer was replaced by a flash tank and an expansion valve on the output on the condenser.
- The fans were replaced with efficient EC fans with permanent magnet motors.

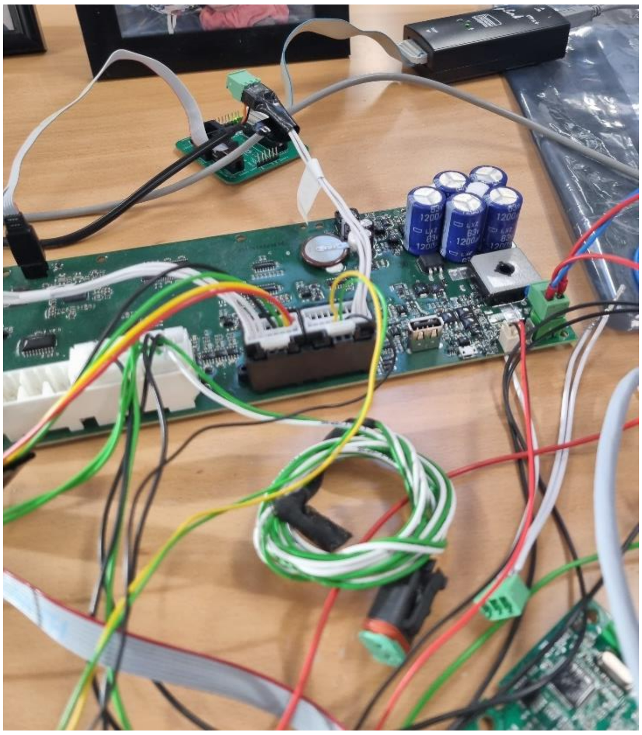
Fit check of prototype inverter to drive the compressor.

4.2 System controller

4.2.1 Main controller development

To control the refrigeration system an embedded controller was needed and for this a new prototype control board was developed. A software design that enables easy reconfiguration to different hardware was developed, making it ready for adaptation to the requirements of future customers. A fast microcontroller was chosen to ensure enough processing power was available to run models of the system on the embedded platform. These models are used to continuously calculate the refrigeration system COP, thus making it possible for the system to optimize its own operation to the best possible energy efficiency.

Another use for these models are for online anomaly detection that can identify problems with the refrigeration system hardware and set an appropriate alarm.



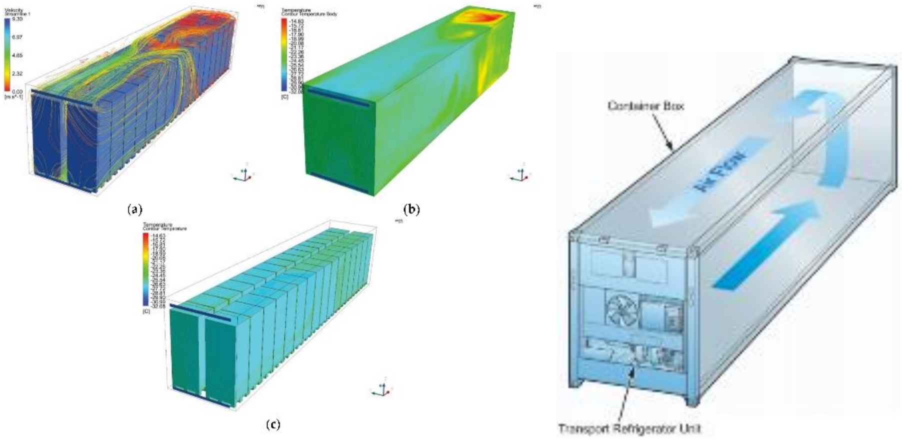
4.2.2 Energy optimization

Early in the project it was found that because the batteries carry a large part of the overall system cost, system efficiency is very important since lowering battery size can significantly decrease cost. Through a series of iterations, where a diesel refrigeration unit was changed it was found that using variable speed fans and an efficient variable speed compressor in a flash gas cycle was the most compact and efficient way of making the system. The refrigeration system on the final eTRU units required advanced control algorithms that had to be developed. The first prototype of the control was tested and verified on the simulation model and then implemented in the embedded controller used to control the system.

After implementation a series of test was performed using the trailer at the test facility, to optimize system energy efficiency in different operating points.

4.2.3 Cargo-hold airflow simulation

A very important part of the energy optimization was reducing the airflow and fan speed to the lowest possible while ensuring a good temperature distribution in the cargo hold of the trailer. SDU developed a COMSOL finite element model of the cargo hold and using this they helped find a good mechanical design for the nozzles on the evaporator fan and the air distribution ducts that are now used in the final units.



Air-flow models from SDU

The model was verified using the air temperature grid measurements from the test trailer, and the identified minimum fan speeds were programmed into the embedded system controller.

4.3 Power topology

4.3.1 Battery pack development

The battery pack was purchased from a local company that already had extensive experience in building such packs that were used on renovation vehicles. For initial testing a battery pack was borrowed, while the custom pack needed for the unit was being built.

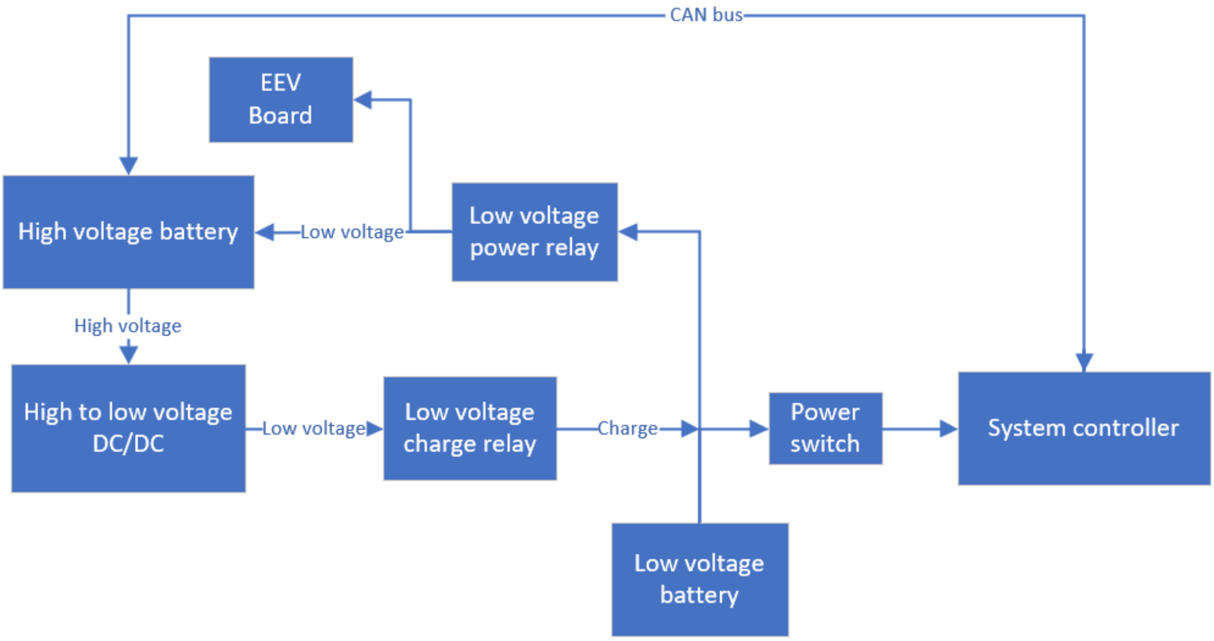
Borrowed battery on the left and final design on the right.

The developed battery was made in cooperation with the supplier to fit into the refrigeration unit. This made it easier to replace existing refrigeration units because the battery didn't need to be fitted to the trailer separately. Due to the long lead time on the battery, it was ordered early in the process before the final refrigeration system was built and the exact capacity requirements were known. It was chosen to fit as much battery capacity as possible to meet as many demanding scenarios as possible and a custom battery pack design was therefore developed. The compact design has a capacity of 51kWh and this has now been shown to be enough for a full workday, even in the most demanding scenarios.

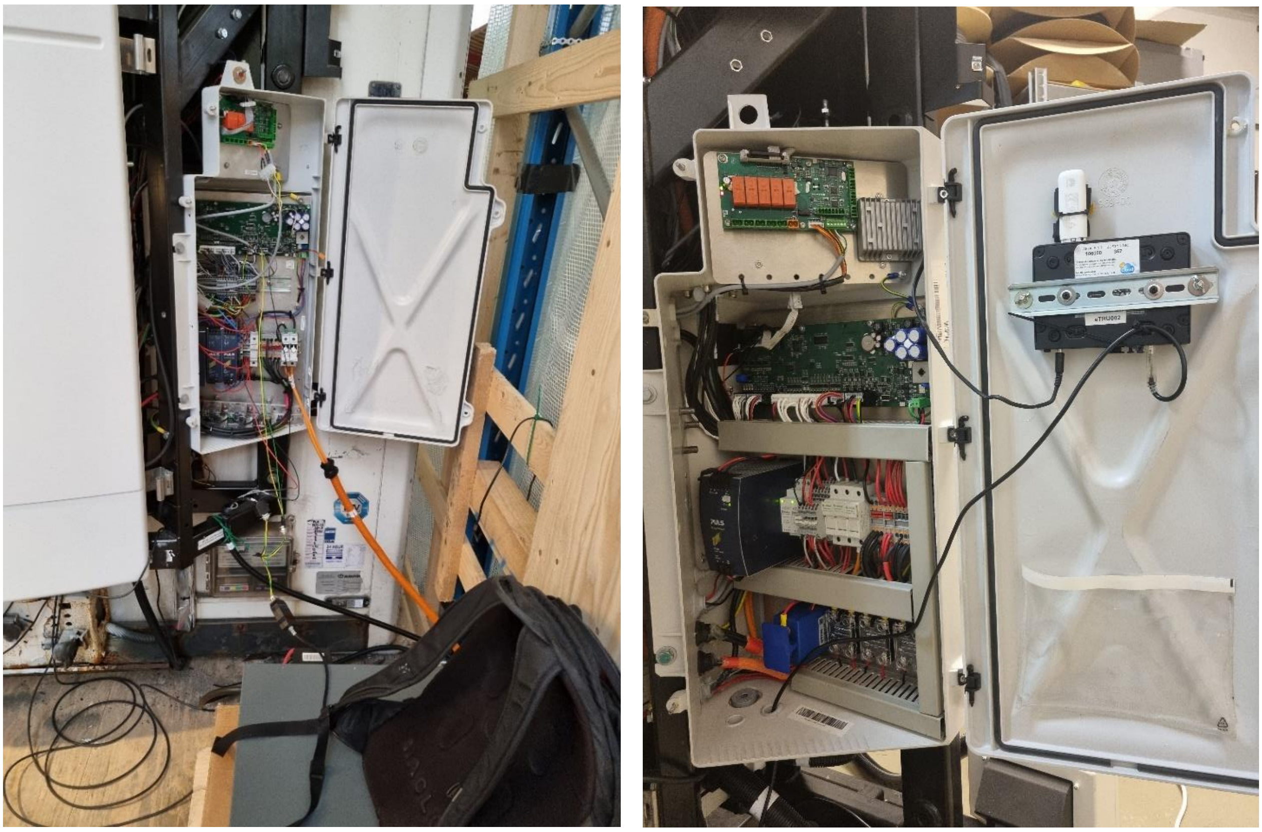
Left: Battery pack in the refrigeration unit frame. Right: topology of battery modules in the pack.

4.3.2 Electrical system design and development

The design of the electrical high and low voltage system for the refrigeration unit went through a couple of iterations before arriving at the current design. The large battery pack requires and external supply to power on and therefor the refrigeration unit has a low voltage system powered by a small battery that can power the unit in start up and safe mode operation where the high voltage battery is turned off. When powering on the unit the controller tries to power up the large battery and if all safety checks are successfully completed the refrigeration unit can start consuming power from the high voltage battery. A DC/DC converter converts power form the high voltage battery to the low voltage and charges the low voltage battery.



The overall concept of the power system design is shown on the figure above. The EEV board is the driver for the electronic expansion valves.



Different iterations of the electrical cabinet evolving from left to right. Left side show the mockup prototype at the test facility and right side show the design used on the road test units. A small PC was added to the road test unit to make it possible to monitor the system closely and collect data during the test.

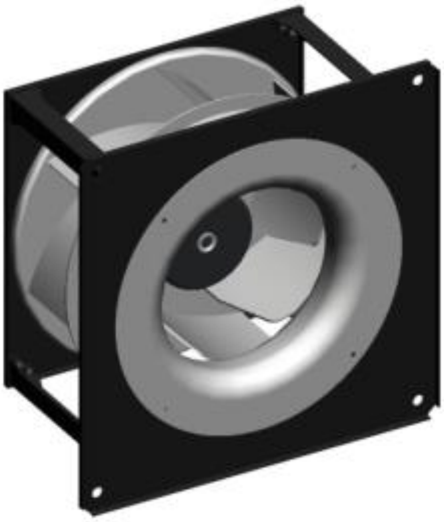
4.3.3 Charger

Initially it was expected that the charge could be staionary and mounted at a wall at the trailer parking lot, but our field test partner wanted to be able to charge on the go since the usage scenarios required charging at multiple locations. Therfore the charger was upgraded with a longer high voltage DC cable and mounted in the pallet box of the trailer as shown on the picture below. This enabled charging at many truck stops where a 32A CEE plug usually is available for running diesel electric units on shore power during the night.

Charger mounted in pallet box, of the trailer.

4.3.4 Fans

To ensure good efficiency variable speed fans were needed instead of the existing fixed speed fans. Unfortunately, it was very difficult to find an off-the-shelf product that was able to run on DC from the high voltage battery and at the same time being fit for running in the environment in the trailer. The fan that was used works well with a DC supply but needed some water proofing modifications to handle the trailer environment.




Using these fans a reduction of fan power consumption of more than 5 times were achieved compared to the fans on the original unit, manly due to being able to run at a lower speed, but also due to the more efficient permanent magnet motors.

4.3.5 Inverter, custom design for DC supply

To drive the compressor a special inverter that can work well from a DC power supply was developed. This work included Schematics, PCB layout, testing and SW development.


Left: Inverter mounted in the eTRU refrigeration unit. Right inverter prototype PCB

4.3.6 EMC testing

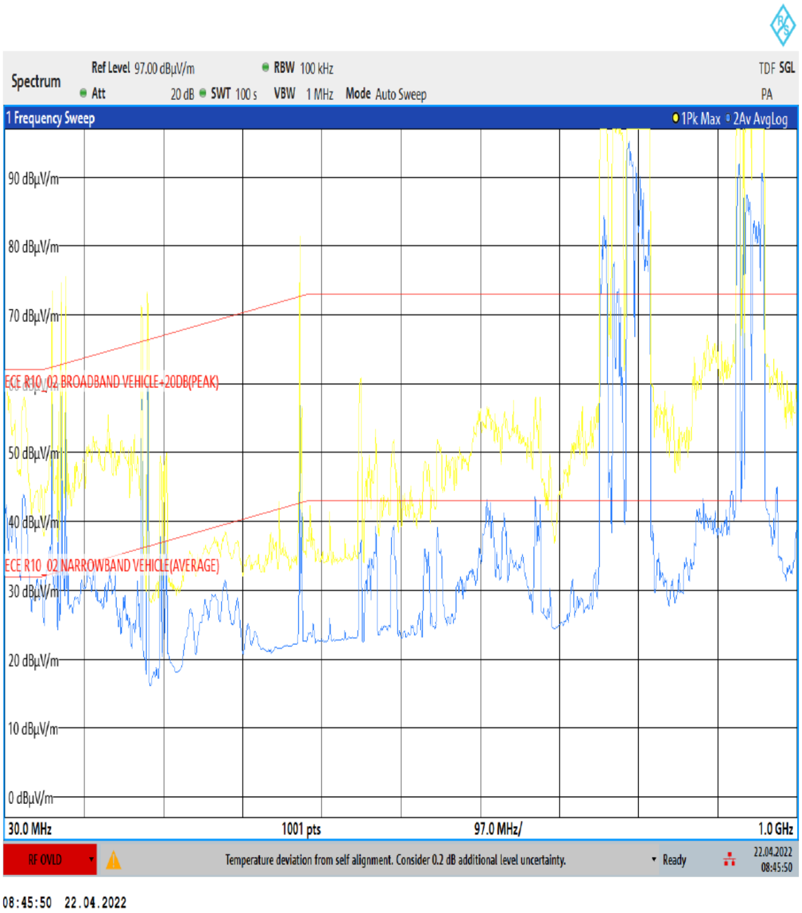
Due to the physical size of the eTRU unit and the wish to create an environment reflecting real life use of a unit were the tests performed outside with a semiportable EMC measurement system modified for the purpose.

The EMC test performed is a pre-compliance radiated EMI measurement on an eTRU (electric Transport Refrigeration Unit). The purpose was to gather data for the radiated EMI level to be used to prepare and if necessary, improve the unit for passing required tests for factory inclusion in a vehicle (in this case a truck cooling trailer) and/or E-marking for aftermarket addition.

The tests were performed as a pre-compliance test according to ECE Regulative R10 of 17/2-2022 EMC requirements for components and separate technical units intended to be fitted in vehicles. The tests were limited to radiated EMI measured at 3m distance as if performed on a vehicle with the EUT fitted, as this should be how the final testing of the EUT is to be performed.

Measurement with a charger attached overview (front horizontal shown)

Measurement is performed under open area test site conditions on a parking lot, as no fully anechoic chamber in a suitable size to accommodate the large EUT and measurement distances was easily available for the project. Measurement was performed on 4 sides (front, back, left and right, as seen from the front) of the EUT with a horizontal distance of 3m from the outer surface of the EUT and the tip of the antenna, and with the antenna centerline 1.8m above the ground. An example of the measured spectra is shown in the figure below.



Spectra for charging and cooling at 100% with setup PC attached, front vertical

Unwanted frequency bands are visible, due to RF-transmitters in the vicinity (for example was the nearest mobile phone mast 300m away from test area and an unknown type of radio mast was also observed~90m from test area). The unwanted contributions were considered when evaluating the results.

The measurements showed that the peak limit, according to the standard, was not exceeded even for the 100% Cooling case, the 100% charging time and the combined case. The 100% cases were considered worst-case scenarios for the eTRU operation.

4.4 Prototyping and operational testing

4.4.1 Distribution scenario testing

To transport goods across borders an ATP approval is required and this is a test of the insulation rate of the trailer and the cooling capacity of the refrigeration system. To ensure that the refrigeration system could pass ATP a series of test designed to mimic the tests conducted during ATP certification were carried out. It was found that that the refrigeration system and trailer could pass the test, with a small margin in frozen mode. To enlarge the margin and ensure successful results in the official test some parameters on the refrigeration system control were adjusted.

Data from a series of trips driven with traditional TRU’s by the road test distribution partner were analyzed and used as a blueprint for a series of tests where the unit was parked but subjected to the same heat load profile as had happened on the road. The main benefit of this test was to verify that there was adequate energy available in the battery to sustain a full day of operation with multiple door openings.

4.4.2 Road test

Scenario road-testing was performed where the refrigeration system was subjected to various strains such as high speed (wind loading), rain and vibration. No serious issues were identified, but some operational parameters of the reefer control SW were adjusted to optimize condenser fan power consumption.

The overall power consumption of the system was not increasing significantly when driving, indicating that our static load test is a good indicator for performance on the road at other temperatures than what was present in the test period.

Road testing with real goods was carried out in and in the test period it was chosen to test the system driving in a fixed route from production facility to a warehouse for unloading During the initial test period the trailer had two trips a day, one loaded and returning unloaded. On most trips the goods received were not on temperature setpoint when loaded and therefore it was important to continue the temperature pulldown process in the trailer during transportation. This loaded the refrigeration system heavily but since high load scenarios were already thoroughly tested this was not a problem, and even though the refrigeration system was running at full capacity for most of the trips the battery capacity was still adequate for a full workday for the driver.

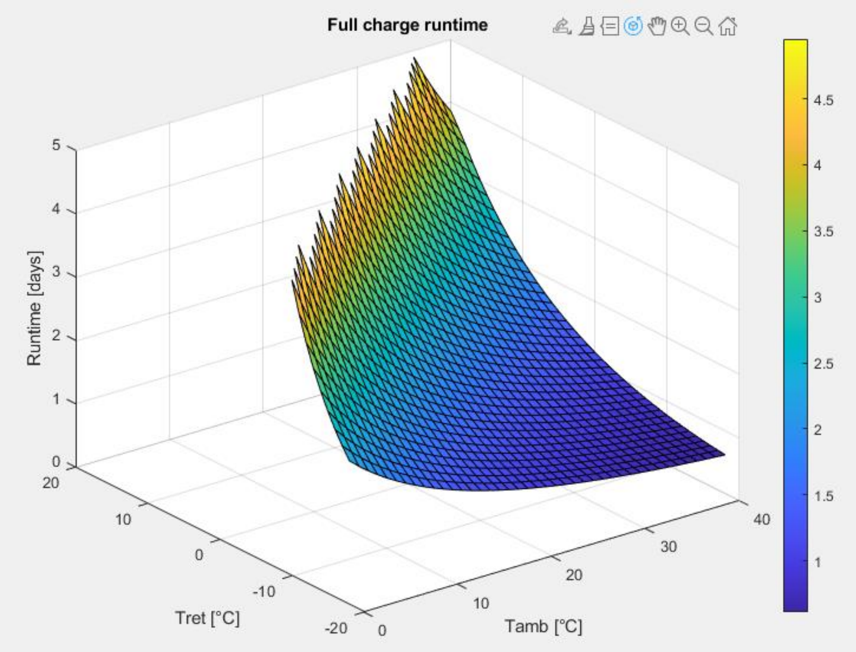
Trailer picked up by Transport company at the beginning of the road test.

Picking up the goods a the production facility

Delivering goods at the warehouse

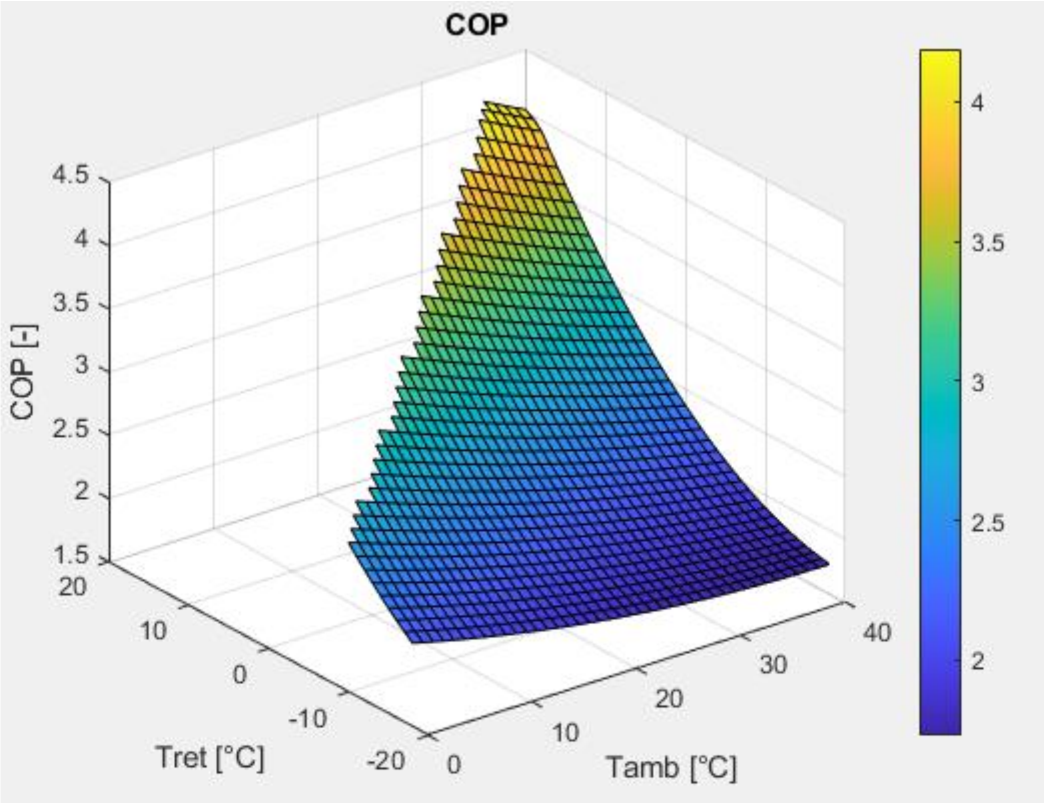
4.4.3 Energy efficiency, runtime.

The unit was tested in different scenarios to verify that the calculated full charge runtime at different temperatures were correct. The trailer we have is old and the insulation is not as good as expected but still the unit manages to run frozen goods at high ambient temperatures for long enough to be used in a distribution scenario. On a new trailer runtime at frozen temperatures is expected to double.



COP test summary

The COP was tested at our test facility where a trailer with an eTRU unit has been equipped with additional sensors to measure heat leakage and extra heaters to simulate increased heat loads. The results are as on the figure below, with a COP that is always significantly higher than that of the original unit that showed a maximum COP of 1.5. The eTRU unit minimum COP is 1.75, and in most cases higher than two due to the system's ability to vary the speed of fans and the compressor according to load requirement. It was verified that the COP matches our theoretical calculations.



4.4.4 Cost comparison

A comparison in cost between running the electrical trailer and a diesel driven trailer was done during the road test. The diesel driven trailer was driving on the same route as the electrical trailer, also doing two loads a day. The diesel unit was the same type and model as the one used to make the electrical unit but the trailer for the diesel unit was brand new where the trailer for the electrical unit was 8 years old. This gives a slight advantage to the diesel unit because the heat loss through the trailer walls is only half as large as for the old trailer used for the electrical unit.

For the diesel unit only one week's diesel consumption was recorded. It had 14 run hours consuming 31 liters of diesel, giving a consumption of 2.21 liter per hour. Converting the electricity consumed to equivalent needed diesel amount using the max conversion efficiency of 30% of the diesel generator, the equivalent diesel amount was 2.20 liter per hour for the electrical unit. So even when a significantly worse trailer is used the electrical power consumed by the eTRU refrigeration system does not exceed the power consumed by the original refrigeration system. Assuming equal power consumption for the two system and a cost of 12,0kr per liter of diesel and 2,5kr per kWh of electricity the energy cost of running the electrical trailer is 62% of the cost for the diesel trailer. And this is in a worst-case scenario where the COP's of the two system are close to each other and the trailer used for the electrical system is in much worse condition than the trailer for the diesel system.

4.4.5 Acoustic noise level measurements

The acoustic noise level measurements have been conducted on the 30th of August 2022 on the outside test field of the BITZER Electronics A/S, near Sønderborg. The measurements were made manually at a 1-meter distance to the eTRU unit according to the DIN EN ISO 9614-2 standard: Determination of sound power levels of noise sources using sound intensity. The measurement equipment was a Brüel&Kjaer (nowadays HBK) 2270 handheld recording and analysis unit in combination with a previously calibrated HBK sound intensity probe kit (type HBK 3654). Note that the microphone components were protected by the corresponding HBK dead cat to account for the outside recording conditions.

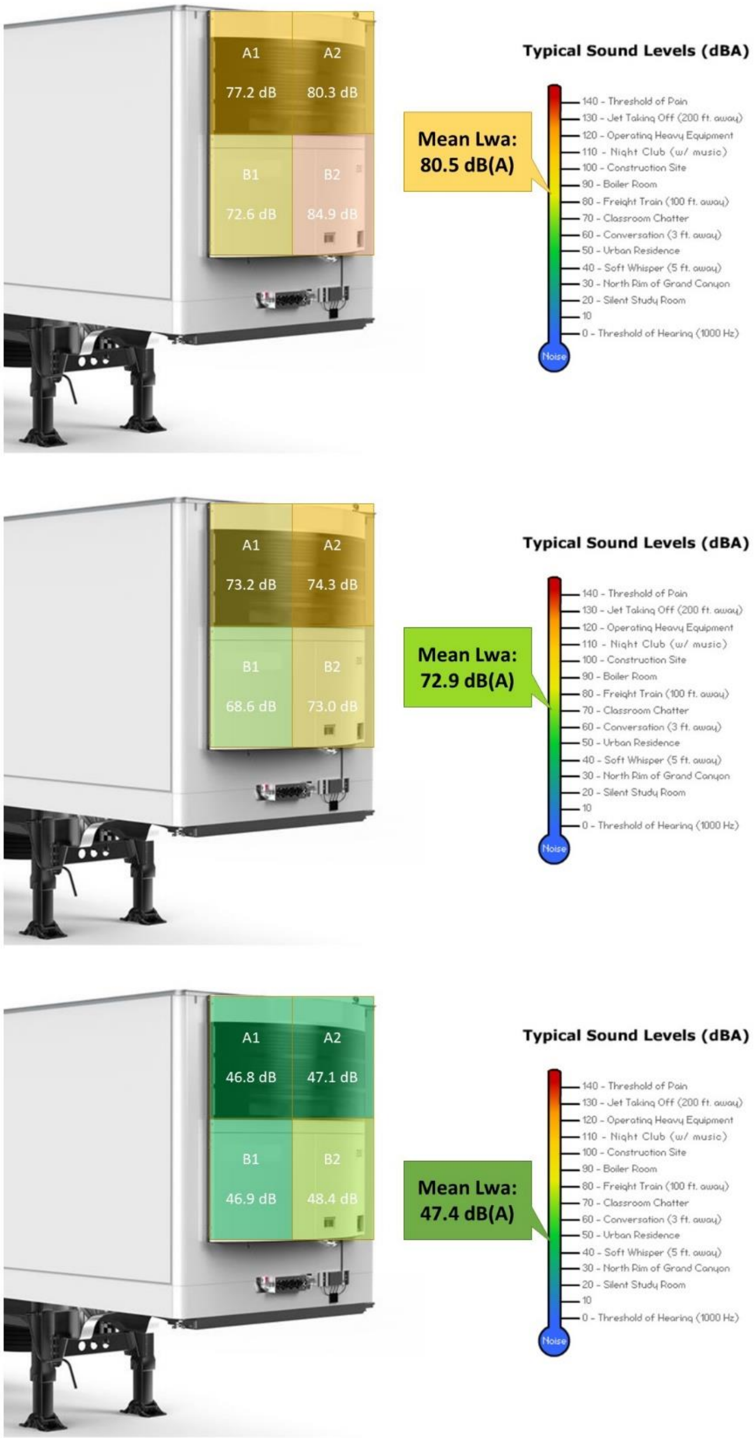
As is shown in the figures below, the measurements were made with the eTRU facing front. Moreover, the front of the device was split up into 4 equally large areas within which the sound characteristics were determined individually. The areas are referred to as A1 (top right), A2 (top left), B1 (bottom right), and B2 (bottom left) below. For the A1 and A2 measurements, the operator (Oliver Niebuhr) was standing on a ladder. For each of the four areas, 20-second continuous sound recordings were made, moving the intensity probe up and down across the area at a constant slow speed. Based on these 20-second recordings, averaged total sound power levels (Lwa) were calculated and expressed in dB(A).

A total of three conditions were measured consecutively:

- Maximum cooler power condition
- Regular (default) cooling setting condition
- Whispering (low power) operation condition

Photos (by Kasper Paasch) illustrated the measurement conditions and procedure at the Bitzer test facility near Sønderborg/DK. Person in charge: Oliver Niebuhr.

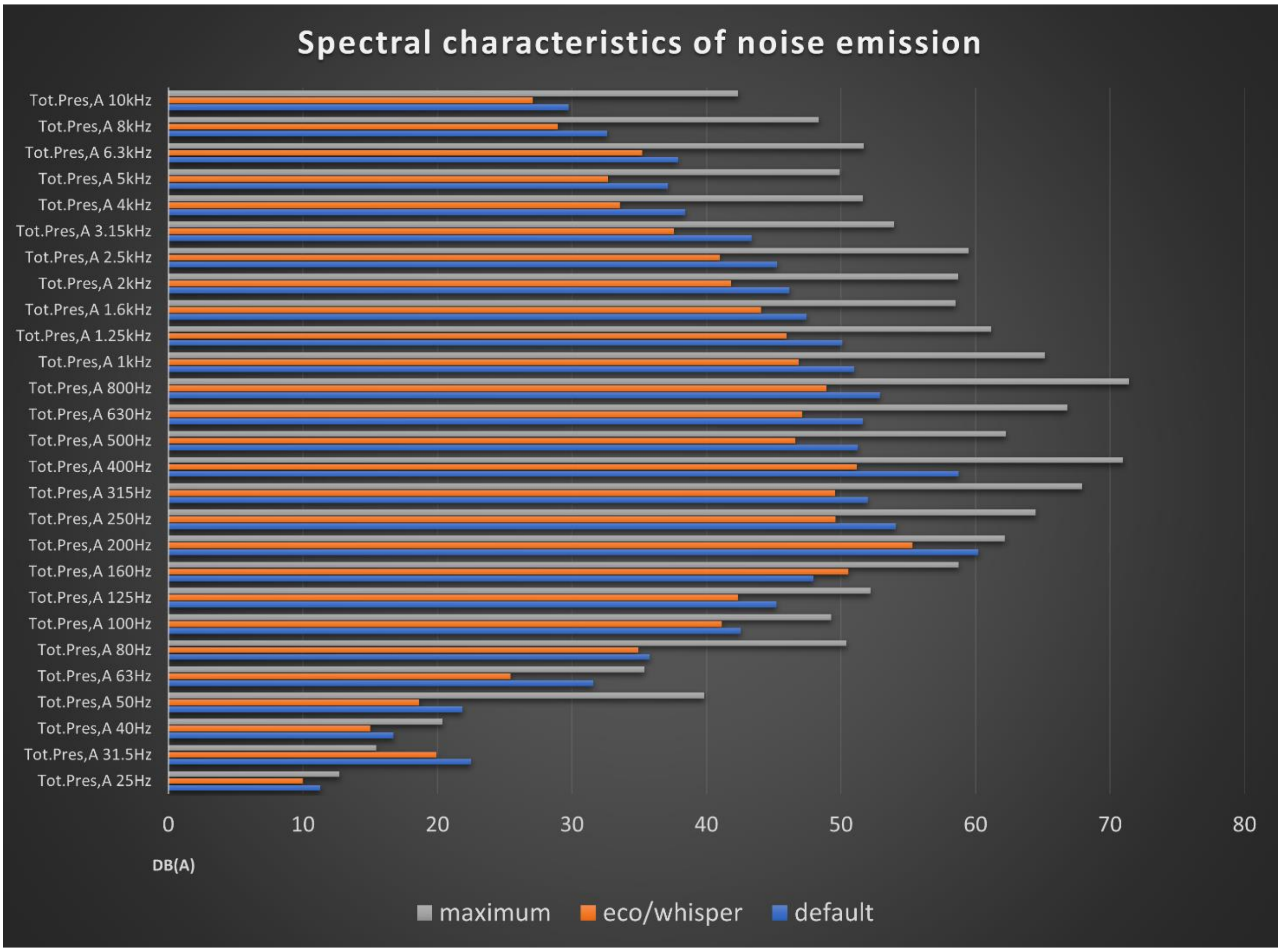
The results of the measurements are summarized in terms of the averaged Lwa values (in dBA) in the figures below. As can be seen the noise emission of the maximally cooling eTRU at a short distance of about 1 meter roughly corresponds to that of a freight train 100 ft away, i.e. 80.5 dB(A). However, with its regular, default cooling setting, the noise emission is already significantly lower. The total mean Lwa decreases by 7.6 dB(A) to only about 72.9 dB(A), hardly more than classroom chatter – and bear in mind that this is measured at a 1-meter distance. In normal traffic situations, the eTRU will probably never get that close to house walls, pedestrians, etc. In the final change to the low-energy (eco/whisper) mode brought about the greatest reduction in noise emission. In this mode, the total Lwa at a 1-meter distance was just 47,4 dB(A), i.e. 25,5 d(B) less than in the regular/default operation mode. At such a noise level, it is likely that most noise emitted by the eTRU will be masked by other surrounding street or environmental noises.



Results of the sound/noise measurements in the three conditions maximum (top), regular (middle), and whisper/eco (bottom).

Note that the results summarized in figures above show some left-right and top-bottom differences. The sound power levels are higher on the right side (A&B2) of the eTRU than on its left side (A&B1). Likewise, the determined sound power levels are higher towards the bottom of the device (B1-2) than at its top (A1-2). These areal difference change with the cooling mode. The maximum cooling mode brings about considerable left-right differences of up to 10 dB(A), especially at the bottom of the eTRU. The top-bottom difference is less strongly pronounced. The exact opposite applies to the regular/default operation mode. In this mode it is the top-bottom difference that more strongly pronounced (5 dBA and more) than the left-right difference. This mode-dependent asymmetric noise emission behavior of the eTRU might be interesting to keep in mind in everyday use – and in implementing future noise-reduction measures. In the eco/whisper mode, the asymmetric noise emissions largely disappear, i.e. they are balanced out. However, in general the top left area of the device is lowest in terms of noise emission; the bottom right area is highest.

Finally, it is potentially relevant to point out that these sound power differences between the three conditions are not equally due to all sections of the acoustic spectrum. As the figure below shows, the three operation conditions produce roughly equal noise emission characteristics until about 100-150 Hz, i.e. in the low part of the sound spectrum. Differences are strongest between 1-2 kHz, and then they successively decrease again towards higher frequencies, especially those between the eco/whisper and default conditions.



Sound emissions of the eTRU in its three modes across the lower half (0-10 kHz) of the audible acoustic spectrum.

Given that the region of high sensitivity of the human ear extends beyond 2 kHz, it can be expected that, in practical use, the perceived differences between the eTRU sound characteristics between the default and the eco/whisper mode are not as big as the mere numbers in figures 11a-c may suggest. In other words, it is possible that the default mode is perceptually closer to the eco/whisper mode than the numbers may suggest. However, to test that must be a task for the future.

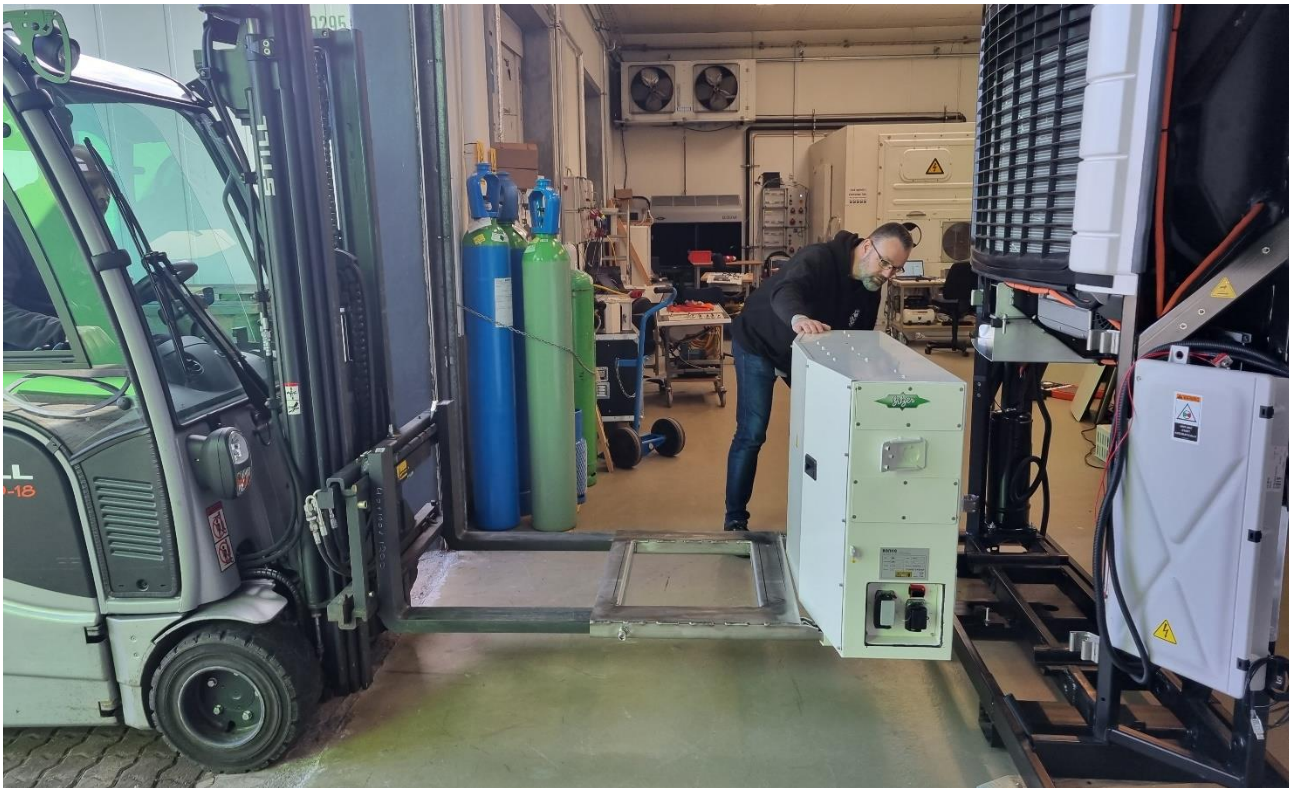
Finally, as regards the limitations of these measurements, note that all values and interpretations reported here have to be treated with some caution and may be considered preliminary. This is mainly for two reasons.

Firstly, the measurements have been conducted outside and are hence inevitably ”contaminated” by environmental noise, e.g., road noise from the nearby highway (B8). Note in particular that, since the measurements were made in the morning between 9-12, this noise source varied and was probably higher for conditions 1 and 3 (maximum and eco; due to rush hours on the road) than for condition 2. Secondly, the truck was placed next to a line of trees and bushes, see figures 10a-c. It is very likely that the observed left-right noise-level differences were to some degree due to that specific placement, because the leaves of the trees made considerable noise – even worse, the wind and hence also this noise source increased in the course of the morning and thus also across the three conditions. However, the operator took as much as care as possible to start and stop the 20-second recordings only during periods of low or no wind.

4.4.6 Production of road test units

When the design of the refrigeration system was settled production of road test units were carried out.

Left: Refrigeration system completed, Right: First unit mounted on trailer.



Battery being installed using forklift adaptor. Changing a faulty battery can be done in 30 minutes if needed.

A road test unit installed in a trailer

Prototype units, before installation in trailer

- *Describe the obtained commercial results. Did the project produce results not expected?*

The commercial environment is now ready for this type of technology – our road test partners are very positive, towards such systems and have given us valuable feedback in terms on which functionalities they see as most value adding for them. Working with the technology has given Bitzer Electronics as well as the transport company a unique insight in the parameters that are important to build a solid business case and a competitive product. This knowledge will be very helpful when searching for the right partner for commercialisation, and to build the systems.

- *Target group and added value for users: Who should the solutions/technologies be sold to (target group)? Describe for each solutions/technology if several.*

We see the target group for this kind of system to be a producer of refrigeration systems for refrigeration trailers. This could be one of the main players in the existing market, or a large corporation wanting to enter and disrupt the market or even a smaller producer that wants to grow its market share through the green transition. The technology developed and demonstrated within this project is far ahead of all other battery driven refrigeration units that has been demonstrated by competitors so far and therefore the company that choose our solution will have a competitive edge.

- *Where and how have the project results been disseminated? Specify which conferences, journals, etc. where the project has been disseminated.*

    - Danish-German PE-Region Platform seminar on battery technologies. 29-03-2022
    - Banke A/S inauguration event with conference on future green tech. 29-06-2022
    - Demonstration of the unit at the 2022 IEA conference in Sønderborg
    - Presentation by managing director Henning H. Kristensen on TV2 news 9/6-2022

5. Utilisation of project results

- *Describe how the obtained technological results will be utilised in the future and by whom.*

The eTRU control electronics and SW will be used in road transport of temperature sensitive goods. The user will be shippers, trucking companies.

- *Describe how the obtained commercial results will be utilised in the future and by whom the results will be commercialised.*

We are still exploring the partnering possibilities.

    - *Did the project so far lead to increased turnover, exports, employment and additional private investments? Do the project partners expect that the project results in increased turnover, exports, employment and additional private investments?*

The project has not yet generated additional turnover, but to execute the project an additional employee was needed. It is expected that when we find the right partner for commercialisation additional employees will be needed to further develop and maintain the product. Increased sales will increase the revenue and if a market share of 15% of the European market is gained this will be a very significant revenue increase for Bitzer electronics. It is expected that the refrigeration units will be built outside Denmark and therefore the export share is expected to be 100%.

- *Describe the competitive situation in the market you expect to enter.*
    - *Are there competing solutions on the market? Specify who the main competitors are and describe their solutions.*

Currently there are no competing products available for sale in the market. Some prototypes have been shown by major players, but all have in common that they consist of existing commercial diesel driven refrigeration units where the diesel generator has been replaced with a battery pack. None of the main players have made integrated systems where the optimization of performance of the refrigeration system and its control algorithms are done.

- *Describe entry or sales barriers and how these are expected to be overcome.*

The main current sales barriers for this battery driven unit are the price of the battery pack. The complete battery driven system will have a higher price point, than the conventional diesel driven unit, this could be overcome by focusing on the TCO instead of the initial investment. The system manufactures are focusing on making as few changes to their existing products and are working with improving efficiency in smaller steps – the manufactures are reluctant to introduce new products where different service competences and spare parts are needed.

- *How does the project results contribute to realise energy policy objectives?*

One of the pillars of the European energy policy is decarbonization of all traffic including road transport and this project demonstrates that decarbonization of most of the refrigerated transport is feasible, and even economically attractive for the shipping businesses.

6. Project conclusion and perspective

In this project it was demonstrated that decarbonization through electrification of refrigerated road transport is technically feasible, and that it can be done without significantly changing the refrigerated trailers used today.

Several existing refrigeration unit frames were stripped and rebuilt with a new refrigeration system, electrical system, control electronics and control software. The refrigeration system was engineered to be more compact and efficient and to achieve more accurate temperature control through better capacity regulation. The resulting refrigeration unit is compatible with existing trailers and can be swapped for a diesel driven one with a few hours of work.

It was found that because the dominating cost of a battery driven transport refrigeration unit is the battery pack, reducing the energy consumption of the refrigeration system is important to lover the TCO of the system because a smaller battery can be used. Therefore, investments in more expensive but energy efficient components that is normally not used on diesel driven refrigeration units makes sense on a battery driven unit.

The project also concludes that with the current battery charging infrastructure in Denmark, an onboard charger is important to improve usability of the battery driven units.

The future perspective of the battery driven system could be to incorporate faster and adjustable charging systems, and even integration into the power grid, as a smart grid integration.

To further improve the competitiveness of the product, further development on how the battery is charged is needed, especially when the battery is charging and needs to be balanced while the refrigeration system is running, due to the fact that the trailer are often loaded, when stationary, so they need to operate also when charging. This will require closer integration of the refrigeration system controls with the battery management system to better coordinate actions and thereby provide a better user experience. It is expected that by adding smart grid functionality the battery can be charged at lower cost, using greener energy and help reduce the peak loads on the grid.

The developed road test units continue to serve as a demonstration of feasibility of the technology to the transport companies and producers of transport refrigeration systems. We will continue running tests with partners in the food distribution business to improve the robustness of the systems and mature the technology further. A running demonstration is important in the effort to sell the technology to a producer of transport refrigeration systems, because the perceived risks of adapting to radically new technology is much smaller if the system is already running in its intended environment.

7. Appendices

Appendix 1	Efficient Operation of an Electrified Transport Refrigeration Unit
Appendix 2	Power Efficiency Optimization of a Transport Refrigeration Unit
Appendix 3	SDU eTRU rapport_1.0
Appendix 4	eTRU project results