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m1 power consumption study

Metro m1 Lausanne

Final report

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Bern, den [06.12.2022]

Content

1. Executive summaries (E, F, D)

Executive summary (E)

The Department of Physics at the University of Basel (DPUB) was commissioned by the transports publics de la région lausannoise (tl) to build a measuring system for the m1 metro in Lausanne. The aim is to analyse the consumption measurements of one year, to work out proposals for energy-saving measures, to implement them if possible and, after a second year of measurements, to check the success of the measures and to transfer the improvements to the entire m1 fleet. A further study listed the general requirements for future energy-efficient vehicles and proposed thoughts on a simple and inexpensive measurement system for new or existing vehicles.

During the development of the measuring system, the DPUB was able to count on the support of the company OPIT Solutions (measuring computer and data server) and the company pi-System (direct current measurement). After the configuration of the components, the system was tested in Basel, installed in train 218 by tl and put into operation in Lausanne with the help of the DPUB.

The first year of measurements showed that the Metro's HVAC system consumed 14.9 % of the total net energy, of which 97 % was for heating. In standby without heating reduction, almost as much heating energy was consumed as in operation.

Of the six energy saving suggestions considered, two relatively simple but very effective measures could be implemented. Sleep mode of the heating (temperature reduction to: 8°C compartments, 17°C driver's cabs) and the reduction of the temperature of the compartments in operation from 18°C to 15°C.

The second year of measurements showed that the HVAC energy was more than halved compared to the first year from 14.9 to 6.5 %, which reduced the total net energy consumed by 8.4 % (Fig. 13). The comparison of the measurement data became more difficult because, in addition to the normal climatic and operational interfering influences, the Corona door opening measures were also added.

In chapter 9, the energy consumption of 15 different vehicles was compared with each other.

This project (November 2018 - December 2022) was supported by the Federal Office of Transport with CHF 188'700 as part of the Energy Strategy 2050 for public transport.

Executive summary (F)

A la demande des Transports publics de la région lausannoise (tl), le Département de Physique de l'Université de Bâle (DPUB) a élaboré un système de mesures pour le métro m1 de Lausanne. L'objectif est d'analyser la consommation électrique durant un an, de proposer des solutions d'économie d'énergie, de les mettre en œuvre et de vérifier leur efficacité après une deuxième année de mesures et, enfin, d'appliquer ces améliorations à toute la flotte. Une étude supplémentaire a dressé la liste des exigences générales pour les futurs véhicules à haute efficacité énergétique et a proposé des réflexions sur un système de mesure simple et peu coûteux pour les véhicules neufs ou existants.

Lors de l'élaboration du système de mesures, le DPUB a pu compter sur le soutien de la société OPIT Solutions (ordinateurs de mesures et serveurs de données) et de la société pi-System (mesure du courant continu). Après la configuration de ses composants, le système a été testé à Bâle, installé par les tl dans la rame 218 et mis en service à Lausanne avec l'aide du DPUB.

La première année de mesures a montré que le système HVAC du métro consommait 14,9 % de l'énergie nette totale, dont 97 % pour le chauffage. Avant la modification des consignes de température, presque autant d'énergie de chauffage était consommée en veille qu'en fonctionnement.

Parmi les six propositions d'économie d'énergie envisagées, deux d'entre elles, relativement simples mais très efficaces, ont été appliquées : la mise en veille du chauffage (réduction de la température en dépôt à 8°C dans la salle voyageurs, à 17°C dans les cabines de conduite) et la baisse de la température dans la salle voyageurs en exploitation de 18 à 15°C.

La deuxième année de mesures a montré que la consommation du système HVAC a été plus que divisée par deux par rapport à la première année, passant de 14,9 à 6,5 %, ce qui a réduit l'énergie nette totale consommée de 8,4 % (Fig. 13). La comparaison des résultats s'est avérée plus difficile, puisqu'aux conditions climatiques et opérationnelles perturbatrices habituelles s'est ajouté le mode d'ouverture des portes lié au coronavirus.

Le chapitre 9 a comparé la consommation d'énergie de 15 véhicules différents.

Ce projet, qui a duré de novembre 2018 à décembre 2022, a été soutenu par l'Office Fédéral des Transports à hauteur de CHF 188'700, et ce dans le cadre de la Stratégie énergétique 2050 des transports publics.

Executive summary (D)

Für die Metro m1 in Lausanne wurde im Auftrag der transports publics de la région lausannoise (tl) vom Departement Physik der Uni Basel (DPUB) eine Messanlage gebaut. Das Ziel ist durch die Analyse der Verbrauchsmessungen eines Jahres, Vorschläge zu Energiesparmassnahmen zu erarbeiten, diese nach Möglichkeit umzusetzen und nach einem zweiten Messjahr den Erfolg der Massnahmen zu überprüfen und die Verbesserungen auf die ganze m1 Flotte zu übertragen. In einer weiteren Studie wurden die allgemeinen Anforderungen an zukünftige energieeffiziente Fahrzeuge aufgelistet und Überlegungen zu einem einfachen und kostengünstigen Messsystem für neue oder bestehende Fahrzeuge vorgeschlagen.

Bei der Entwicklung des Messsystems konnte das DPUB auf die Unterstützung der Firma OPIT Solutions (Messcomputer und Datenserver) und der Firma pi-System (Gleichstrommessung) zählen. Nach der Konfiguration der Komponenten wurde das System in Basel getestet, von den tl in den Zug 218 eingebaut und in Lausanne mit Hilfe des DPUB in Betrieb genommen.

Die Messungen im ersten Jahr ergaben, dass das HLK-System der Metro 14,9 % der gesamten Nettoenergie verbrauchte, davon 97 % für die Heizung. Im Standby ohne Heizungsreduzierung wurde fast so viel Heizenergie verbraucht wie im Betrieb.

Von den sechs in Betracht gezogenen Energiesparvorschlägen konnten zwei relativ einfache jedoch sehr effektive Massnahmen umgesetzt werden. Der Schlummerbetrieb der Heizung (Temperaturabsenkung auf: 8°C Abteile, 17°C Führerstände) und die Senkung der Temperatur der Abteile im Betrieb von 18°C auf 15°C.

Im zweiten Jahr der Messungen zeigte sich, dass die HLK-Energie im Vergleich zum ersten Jahr von 14,9 auf 6,5 % mehr als halbiert werden konnte, was den gesamten Nettoenergieverbrauch um 8,4 % reduzierte (Fig. 13). Der Vergleich der Messdaten wurde dadurch erschwert, dass zu den normalen klimatischen und betrieblichen Störeinflüssen auch noch die Corona-Türöffnungsmaßnahmen hinzukamen.

In Kapitel 9 wurde der Energieverbrauch von 15 unterschiedlichen Fahrzeugen miteinander verglichen.

Dieses Projekt (November 2018 – Dezember 2022) wurde im Rahmen der Energiestrategie 2050 des öffentlichen Verkehrs vom Bundesamt für Verkehr mit CHF 188'700 unterstützt.

Fig. 1: The m1 metro in Lausanne runs mainly above ground (photo tl)

Participating organisations:

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Federal Office of Transport FOT

tl

UNI BASEL

OPIT SOLUTIONS

pisystem

2. Initial situation

tl operates public transport in the Lausanne region. There is a well-developed bus network with trolley- and diesel buses, a train line and also two metro lines m1 and m2. A new tram line (t1) is under construction and a new metro line (m3) is planned.

Following the study on the energy efficiency of trolleybuses carried out by Jérôme Grand and Philippe Seydoux from 2013 to 2018 as part of the ESPT 2050 program (P-002) together with DPUB, tl had the idea of carrying out a similar project for the m1 trains. The m1 metro runs on the 7.8 km route between Lausanne-Flon and Renens-Gare, providing good public transport connections to the Université de Lausanne and EPFL.

This project was supported by the Federal Office of Transport with CHF 188'700.- as part of the Energy Strategy 2050 for public transport. tl contributed CHF 27'061.- and the DPUB CHF 226'246.- as own funds. The project started in November 2018 and will be completed by the end of 2022 at the latest.

3. Goals

- Recording of the annual energy consumption of the HVAC, the traction/recuperation, the auxiliary operations and environmental data (operating mode, location, temperatures, solar radiation, CO_2 level, etc.)
- Identification and implementation of energy-saving measures with subsequent annual control measurement
- Optimisation of the existing rolling stock (entire m1 fleet)
- Findings for the procurement of new rolling stock
- General study on simpler measurement technology and defining requirements for energy-efficient vehicles

4. Method and time scheduling

- 2014: launching ESPT 2050 program → improving the energy efficiency of Swiss public transport
- 2018: partnership between FOT, University of Basel and tl → energy efficiency study of m1 trains (Development and test setup of the measurement system by the University of Basel)
- 2019: installation of the measurement system in train 218
- 2020: first year of measurements and analysis of improvement potential
- 2021: second year of measurements with parameter optimization
- 2022: conclusions and deployment on all trains

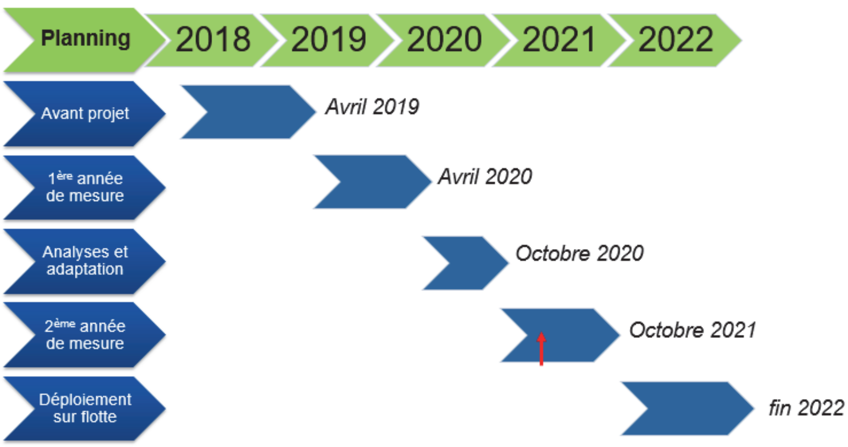

Fig. 2: Time schedule

5. Train 218 measurement system

- Installation in 2019 on metro m1 train 218 (type: TSOL III)
- 57 sensors and 26 devices:
    - System developed by DPUB (Department of Physics, University Basel)
    - Installed by tl
- Two sensor categories:
    - Sensors measuring the external and internal conditions of use (position, speed, temperature, humidity, solar radiation, CO_2-level and door states)
    - Sensors measuring the electrical consumption of equipment (traction, HVAC, auxiliaries: 24 V DC, 230 V AC and 750 V DC consumers separately)

Fig. 3: Overview of the sensors and devices installed on the train 218 (all photos AT University of Basel)

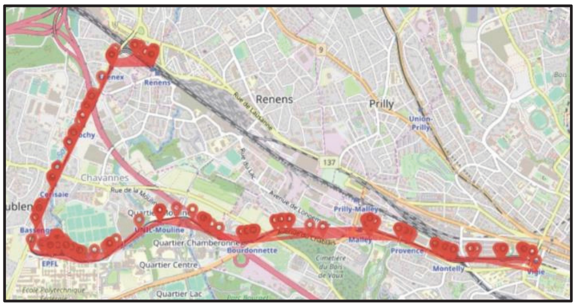

Fig. 4: Real-time tracking of the train's position

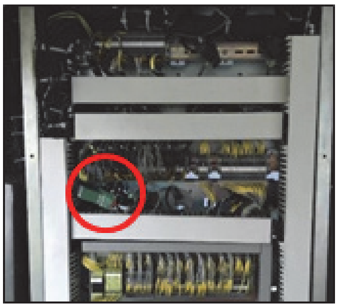

Fig. 5: Current sensor in the driver's cabinet

Fig. 6: Temperature / humidity sensor (1 of 8)

Fig. 7: GPS and mobile communications antenna

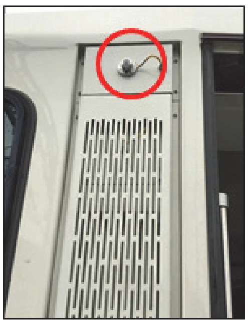

Fig. 8: Solar radiation sensor (1 of 2)

Fig. 9: Brain of the measuring system

5.1 Technical explanation of the metro m1 and the measuring system of DPUB

The metro m1 from tl is a two-car commuter train with two driver cabins and two connected compartments with six doors on both sides. The compartments are heated with fan heaters and are only passively ventilated via windows, doors and roof openings (inside the roof only). Both driver's cabs have air conditioning, heating is also done by fan heaters. During rush hours, 2 such trains can be coupled together to form a composition.

The primary energy of the metro comes from the 750 V DC overhead line (catenary) and is used for traction, heating and the static converter. The static converter in turn provides battery charging (24 V DC), powers the 24 V DC mains (lighting, information system, doors, controllers) and includes a 3-phase inverter (3 x 230V 50 Hz) for the air compressor (brakes, air springs) and air conditioners of the drivers' cabs. When electric braking energy is recovered - a small part is used in the metro, a large part is fed back into the overhead line and the rest heats onboard braking resistors so that the overhead line voltage does not rise too much. See also Appendix A17 - block schematic.

The measuring system collects data of interest every minute all the time and sends it to a data centre at 03:00 each night. The data is rearranged and the over 400 resulting different data points are edited, recalculated and grouped in the data centre so that the evaluation and export of the essential data is easier possible. The system is measuring energy values, door openings, CO_2 values, climate values and position data with GPS. The hardware consists of a measuring computer with mobile modem from OPIT Solutions, who also provide the data centre, a Beckhoff industrial measuring system with software from pi-System, several AC energy meters and many sensors. It measures in continuous operation and is supplied with energy from the vehicle battery. The system was developed by DPUB specifically for the metro, the parts were purchased, assembled as a test setup, documented and finally installed in the vehicle by tl. The position of the devices and the sensors was determined beforehand between DPUB and tl.

5.2 Previous work

- Project start 1. Nov 2018, after signing the contract
- Planning and procurement of the components of the measuring system
- Adaptions and self-construction of measuring components
- Inspection and definition of the installation locations in the vehicle together with tl
- Preparation of plans (block diagram, installation plan, component description)
- System specification for the programming of the Beckhoff DC measuring system for the company pi-System
- Cooperation with the company OPIT Solutions for the installation of the measuring computer and the data centre
- Commissioning of test setup in Basel, intensive cooperation with OPIT and pi-System
- Disassembly of the test setup and delivery to tl
- Installation of the measuring system by tl
- Commissioning of the measuring system in the m1 workshop at Ecublens (GAT m1) on 4.4.2019
- The metro has been in daily use since the end of April 2019 and the measuring system is running continuously
- The necessary preparations in the data centre for the weekly manual validation of the measured values of the metro is done and monitoring is ongoing
- Many measurement points and diagrams on the variables of interest have already been compiled by DPUB in the data centre and initial analyses carried out

6 Results of first year of measurement

The diagram on the left shows the measured energy values of the first year of measurement, broken down by main groups and subgroups, with the percentage shares. The gross energy minus the braking energy fed back into the overhead line (consumed by neighbouring trains) results in the effectively consumed net energy, which is the 100 % reference. Part of the recovered energy is used directly internally by the HVAC and auxiliary equipment.

The pie chart on the right shows how much net energy is consumed in operation (green) and at standby (orange). Here, only the 3 main groups traction, HVAC and auxiliary are shown.

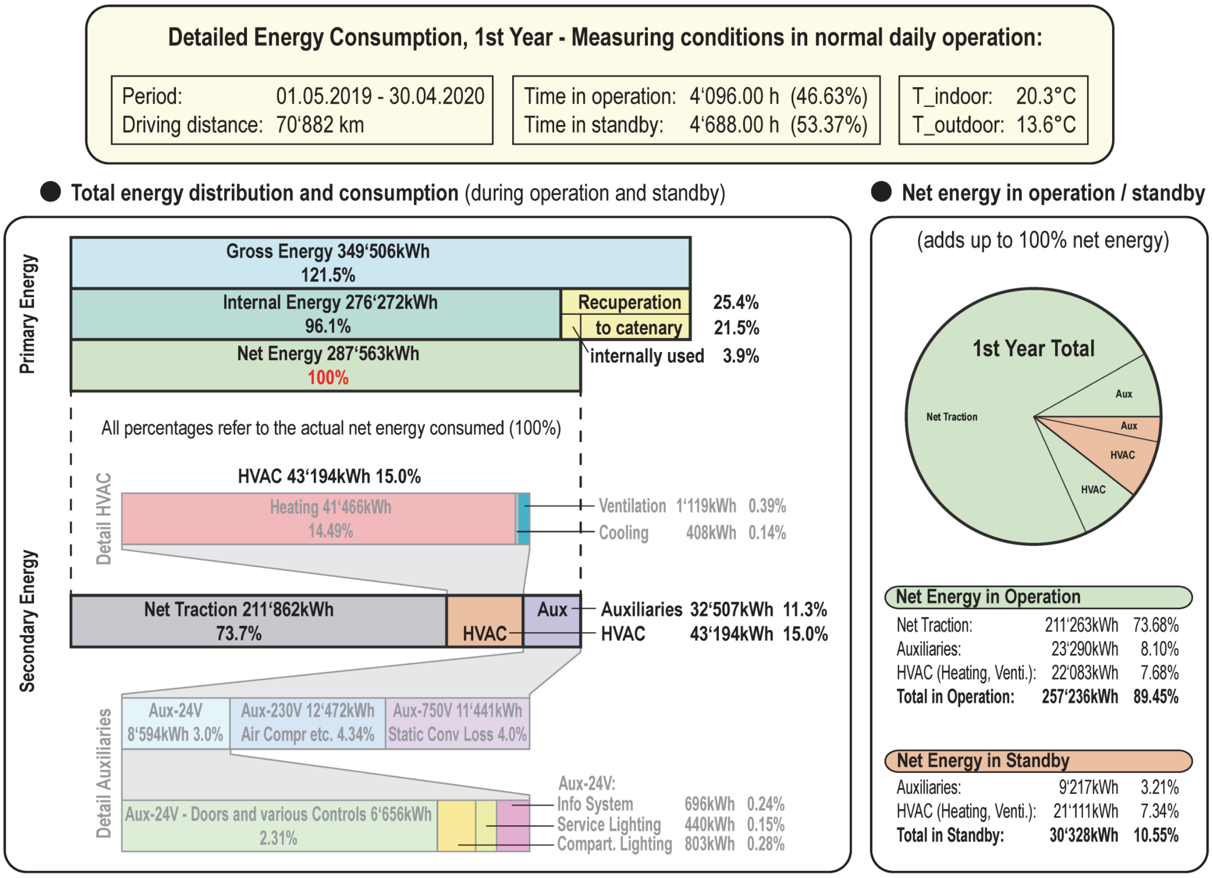

Fig.10: Energy distribution and net energy OP/SB first year

The main part of the net energy (100%) was used by traction (73.7 %).

For heating and ventilation 14.9 % of the energy was consumed. It was a surprise that the cooling of the two driver cabs used 0.14 % of the net energy only, although the summer was very hot.

Auxiliary units, on the other hand, consumed 11.3 % of net energy, where the included lighting and information system consumed 0.67 % only. It was found that the rest of the auxiliary energy was used by the air compressor (4.3 %), the electrical loss of the static converter (4.0 %), the door motors and various controls (2.3 %).

The pie chart shows how the net energy is used when the metro is in park position (52 % of the time). 10.6 % of the net energy were used in standby (park position). The main part of 7.3 % is consumed by the HVAC (mostly heating) which has no sleeping mode. So almost the same amount of HVAC energy was used in standby as in operation! The auxiliary units consume 3.2 % of the net energy in standby via the static converter with an average load of 2 kW at the input. About 600 W are required continuously at the 24V output of the static converter, the sporadic use of the air compressor and the standby loss of the static converter correspond to the remainder of 1'400 W on average.

For more detailed diagrams see also Appendix A1+A2 and A11+A12.

From April 2020, the Corona door opening measures began to improve the ventilation of the compartments in the stations, which led to higher heating energy requirements and had to be taken into account in the evaluations. See also page 13, point 7.3.

6.1 Energy saving proposals and implementation

After the first measurement year (without April[1]), a list of energy saving proposals was prepared by DPUB. The energy saving potential of the proposals P1 - P4 was calculated by simulations, that of the proposals P5 and P6 was estimated cautiously. Different combinations of the energy saving proposals were also examined, as the effects overlap in part.

						(Net Energy = 267'153 kWh)	
						Energy saving over 11 months	
Proposal	Effort	Description	works in	in comb. with	Period	[kWh]	[%] of Net Energy
P1	medium	Complete switch off during standby	standby		May 19 - Oct 19	6'455	2.42%
P2	medium	Setpoint Ti=8°C during standby	standby		May 19 - Mar 20	17'207	6.44%
P2		Setpoint Ti=8°C during standby	standby	P1	Nov 19 - Mar 20	14'905	5.58%
P3	medium	Setpoint Ti-3°C during operation	operation		May 19 - Mar 20	10'558	3.95%
P2+P3	medium	Combination 1	stand+oper		May 19 - Mar 20	27'766	10.39%
P1+P2+P3	medium	Combination 2	stand+oper		May 19 - Mar 20	31'918	11.95%
P4-s		double glacing - 18.1% better ins. (standby)	standby	P4-o	May 19 - Mar 20	4'358	1.63%
P4-s		double glacing - 18.1% better ins. (standby)	standby	P1	Nov 19 - Mar 20	3'771	1.41%
P4-o		double glacing - 18.1% better ins. (operation)	operation	P4-s	May 19 - Mar 20	6'782	2.54%
P4	high	double glacing - 18.1% better ins. (stand+oper)	stand+oper		May 19 - Mar 20	11'140	4.17%
P1+P4		Combination 3	stand+oper		May 19 - Mar 20	17'008	6.37%
P2+P4-s		Interim result 1	standby	P3+P4-o	May 19 - Mar 20	17'954	6.72%
P2+P4-s		Interim result 2	standby	P1	Nov 19 - Mar 20	15'626	5.85%
P2+P4		Combination 4	stand+oper		May 19 - Mar 20	24'736	9.26%
P1+P2+P4		Combination 5	stand+oper		May 19 - Mar 20	28'862	10.80%
P3+P4-o		Interim result 3	operation	P2+P4-s	May 19 - Mar 20	14'679	5.49%
P3+P4		Combination 6	stand+oper		May 19 - Mar 20	19'037	7.13%
P1+P3+P4		Combination 7	stand+oper		May 19 - Mar 20	24'905	9.32%
P2+P3+P4	high	Combination 8	stand+oper		May 19 - Mar 20	32'633	12.21%
P1+P2+P3+P4	high	Combination 9	stand+oper		May 19 - Mar 20	36'759	13.76%
P5	medium	Eco driving	operation		May 19 - Oct 19	5'343	2.00%
P6	medium+	Heating with braking energy	operation		May 19 - Oct 19	2'672	1.00%
P2+P3+P5	medium	Combination 10	operation		May 19 - Oct 19	33'109	12.39%
P1+P2+P3+P5	medium	Combination 11	operation		May 19 - Oct 19	37'261	13.95%
P1+P2+P3+P5+P6	medium+	Combination 12	operation		May 19 - Oct 19	39'933	14.95%
all proposals	very high	Combination 13	stand+oper		May 19 - Mar 20	44'774	16.76%

Fig. 11: Energy saving proposals

The table above shows the energy saving potential of all six energy saving proposals and some possible combinations. The most important individual proposals and combinations have been highlighted in colour according to their feasibility.

Some further explanation of the proposals:

- P1 (complete switch-off during standby) could not be implemented for various reasons (cold-start problems, nightly cleaning, door opening, air compressor...)
- P2 (low temperature during standby) was only fully applied in the compartments and partially in the driver's cabs (P2'), but can be interrupted during night-time cleaning work
- P3 (reduced temperature during operation) was only applied in the compartments
- P4 (better insulation by double glazing windows and doors) was not realized because of its great effort and the fact that together with simpler proposals it has less impact (resulting in a long-term return of 57 years). See also Appendix A10.
- P5 (ecological driving) was not applied due to the tight schedule that left no room for ecological driving
- P6 (heating with brake energy) would only have been effective in winter and is technically more demanding

During 2020, tl implemented the following 3 energy-saving measures on the train:

1. lowering of the heating setpoint of the compartments by 3°C during operation (P3)
2. reduction of the heating setpoint of the compartments to 8°C in standby mode (P2)
3. reduction of the heating setpoint of the driver's cabins to about 18°C in standby mode (P2')

For measures P2 and P3, an energy saving potential of 10.4 % on the net energy was calculated. Since the two measures were not fully applied to the driver's cabs and are interrupted by the nightly cleaning work in the compartments (heating up for drying), the savings are likely to be somewhat smaller.

[1] In April of the first measurement year, the corona door opening measures began

7 Second year of measurements

The diagram on the left shows the measured energy values of the second year of measurement, broken down by main groups and subgroups, with the percentage shares. The gross energy minus the braking energy fed back into the overhead line (consumed by neighbouring trains) results in the effectively consumed net energy, which is the 100 % reference. Part of the recovered energy is used directly internally by the HVAC and auxiliary equipment.

The pie chart on the right shows how much net energy is consumed in operation (green) and at standby (orange). Here, only the 3 main groups traction, HVAC and auxiliary are shown.

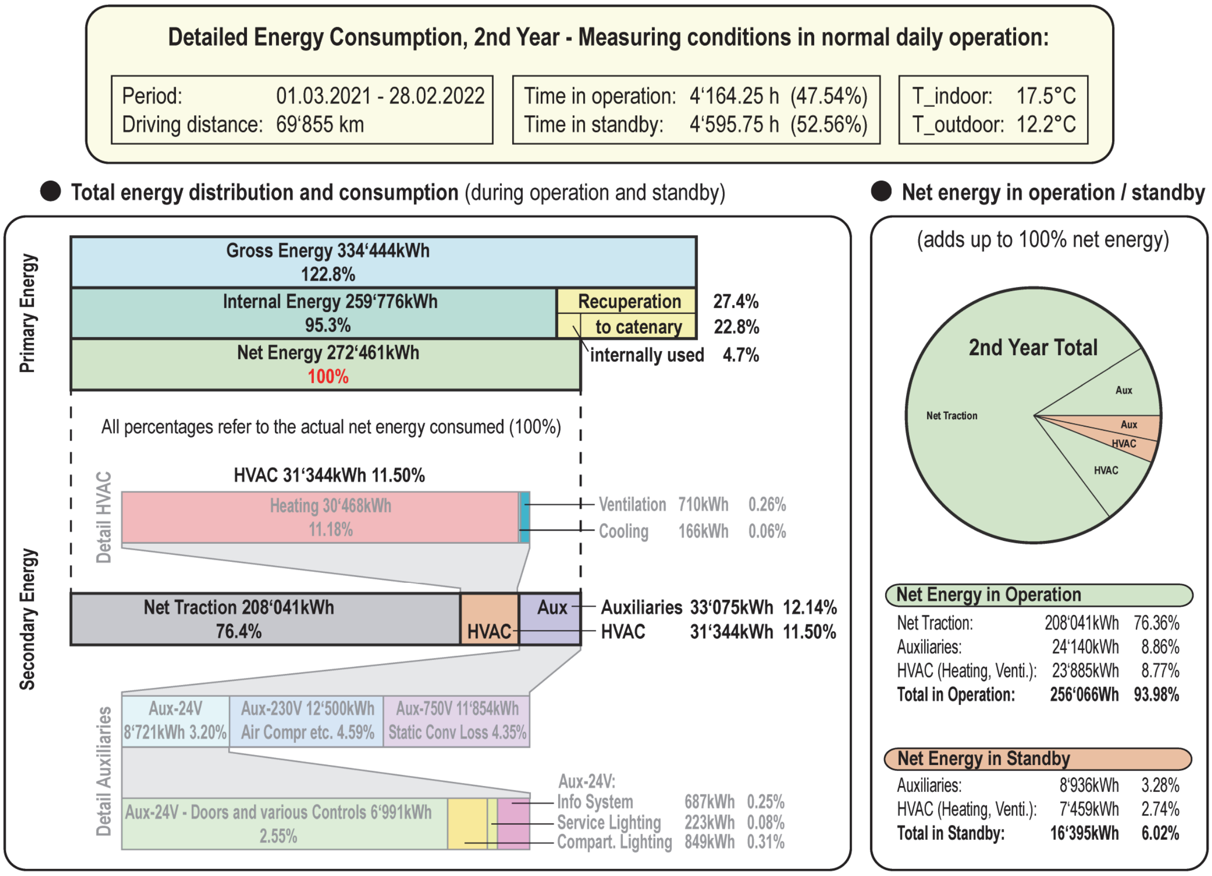

Fig. 12: Energy distribution and net energy OP/SB second year

Compared to the 1st measurement year, the following changes in the main groups result:

- Traction: 16'496 kWh less energy (1'027 km less driving), 2.7 % more share (76.4 %)
- Auxiliaries: 538 kWh more energy (68 h more operation), 0.84 % more share (12.1 %)
- HVAC: 11'850 kWh less energy (despite colder and Corona), 3.5 % less share (11.5 %)

The net energy has decreased compared to the first year in standby by 13'966 kWh from 30'328 kWh (-46 %), but increased by 1'802 kWh in operation (+8 %).

The energy saving measures applied only concern the heating and ventilation part of the HVAC. With the direct measurements, it is impossible to determine the exact energy savings. In addition to the differences in climate, driving performance, operating time and solar radiation, the Corona door opening measures (April 2020 - April 2022) distort the energy savings, especially in the second year of measurement. For more detailed diagrams see also Appendix A11+A12.

By comparing the specific heating power diagrams of three periods with or without heating measures or Corona door opening measures of the compartments, the influence of the Corona door opening measures on the linear trend line equations could be determined.

In the next chapter, a method is briefly explained to determine the energy savings despite all interfering influences.

7.1 Solution approach for a correct comparison

In a complex procedure, many specific heating power diagrams had to be created for both measurement years in function of the temperature difference inside minus outside and the outside temperature for:

- compartments / driver's cabins = cabs (different climate zones)
- standby / operation (mode)
- with / without solar influence (possible by the measured solar radiation values)
- with / without corona door measures (depending on the period)
- with / without energy saving measures (depending on the period)

With the linear trend line equations of these specific heating power diagrams, various simulations became possible. The following is a very simplified explanation of the method:
First, the linear trend line equations were used to simulate the heating power as a function of the outdoor temperature in each of its own years (15-minute steps), summed up to the annual heating energy and all formulas were calibrated with a small offset of the equations to the same result as the measured annual energy. Now the heating power could be determined with the heating formulas of the second year with the outside temperature of the first year under exactly the same conditions of the first year with consideration of all disturbing influences (outside temperature, Corona measures, operating mode, heating location, solar influence). The ventilation energy of the fan heaters was simulated with another formula, the energy of the traction and auxiliary operations was taken from the first year of measurement. The heating energy of both years could now be completely freed from the Corona door opening influence and cleanly separated according to location (compartment / driver's cabs) and operating mode.
For more information see also Appendix A13 – A16.

7.2 Realised energy savings

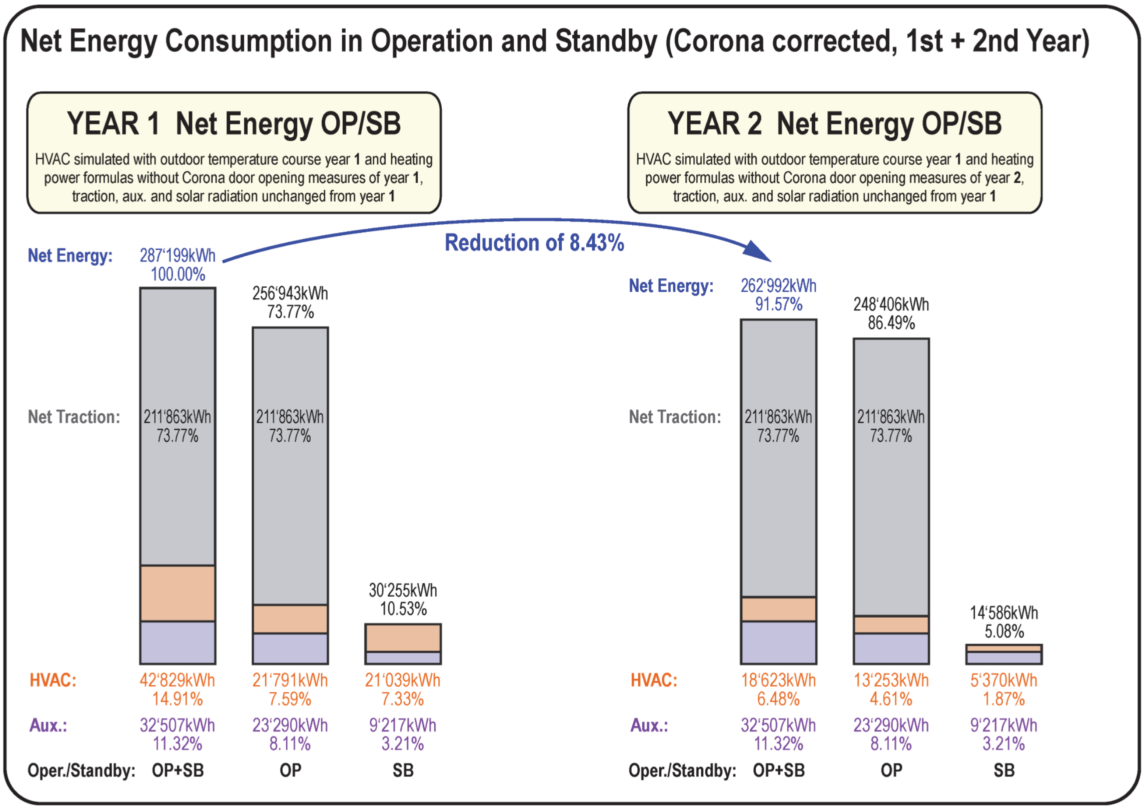

Fig. 13: Net energy savings between the first and second year of measurement

The largest bar in the graph of each year represents the total net energy for that year (OP+SB). The net energy saving from year 1 to year 2 is 8.43 % (24'206 kWh: 8'537 kWh in OP, 15'669 kWh in SB). This is about 2 % less saving than expected in the simulations (measures P2 and P3) after the first year of measurement in chapter 6.1. The reason for this is that measures P2 and P3 could not be fully applied to the driver cabins (cabs). Only the simulated HVAC energy (orange) has changed from the first to the second year according to the improved heating behaviour. Traction energy (grey) and auxiliary energy (purple) remain unchanged.

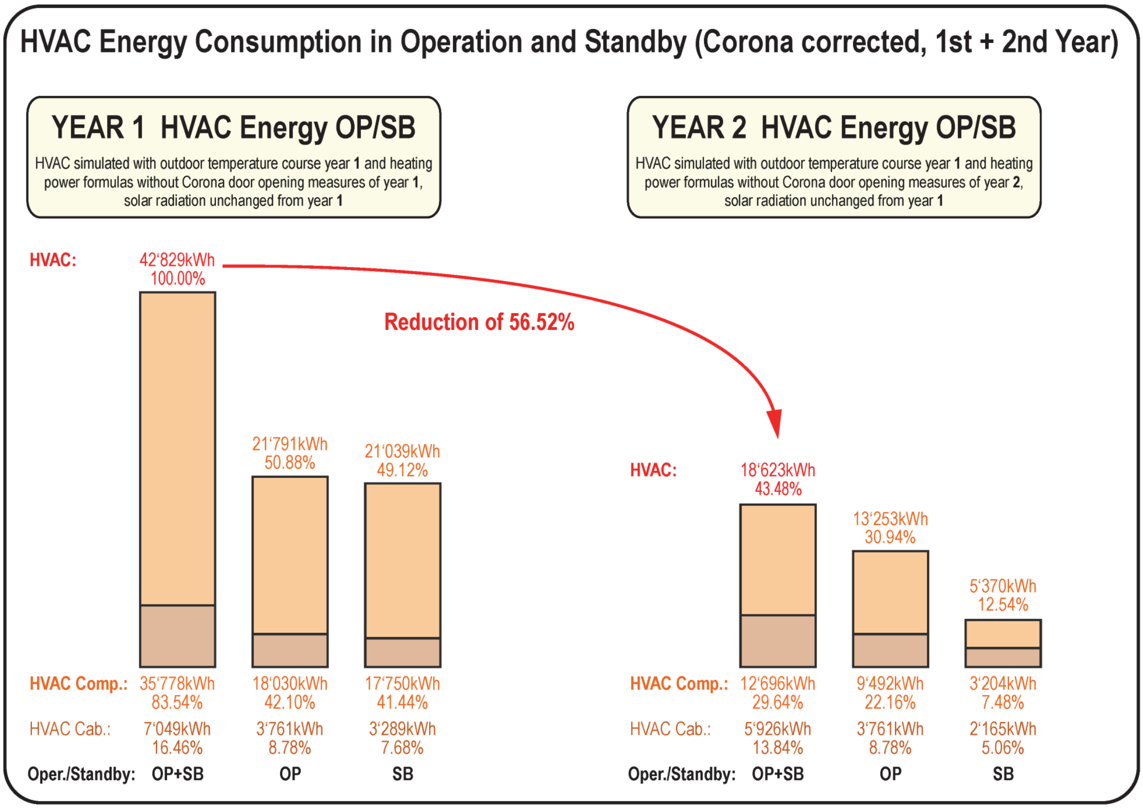

Fig. 14: HVAC energy savings between the first and second year of measurement

The largest bar in each year's graph represents the total HVAC energy for that year (OP+SB). The HVAC energy savings from year 1 to year 2 is 56.5 % (24’206 kWh) - more than half was saved. This is much more than the estimated 10 % - 25 % at the start of the project.

The light part of the bars indicates the energy share of the compartments, the dark part that of the cabs. In the cabs, only a small part of the energy was saved in standby mode (34.2 %, 1'124 kWh). In contrast, in the compartments 81.9% (15'669 kWh) of the HVAC energy was saved in standby and 47.4 % (5'334 kWh) in operation compared to the previous year (thanks to 3°C temperature reduction).

In the diagram of the first year, it is noticeable that about the same amount of HVAC energy is consumed in standby (SB) as in operation (OP) - this is unnecessary and has been improved by the standby sleep mode (temperature reduction to 8°C in the compartments and 17°C in the cabs).

7.3 Effect of Corona door opening measures

The Corona door opening measures were introduced from April 2020 to improve air quality. The second year (Corona) with 1.3 times longer door opening times has a lower CO_2-concentration compared to the first year (no Corona) - a sign of better air quality.
575 ppm CO_2 corresponds to very good air quality.

Annual average numbers

Year	Door opening	CO2-Level
	[%]	[ppm]
Year 1	17.36	732
Year 2	22.62	575

Explanations (Year 1 without April 2020):
- At a door opening of 100% all 12 doors would be open all the time
- Door opening and CO2-level are averaged during operation only
- Minimal CO2 level is around 400 ppm (clean air at night)

Fig. 15: Corona door opening measures

Because of these measures, all six doors on one side were automatically opened at each station and all twelve doors on both sides at the terminus stations. Only on very cold days were the measures relaxed somewhat.

In the diagram on the right, the annual net energy of both years was simulated with and without corona door opening measures.
Since only the transition month of April was affected in the first year, the measures led to an additional consumption of only 0.13 % of the total net energy. With the year-round Corona measures during the second year, the total energy increased by 1.52 % (all comparisons are made with the first year without Corona measures as reference).

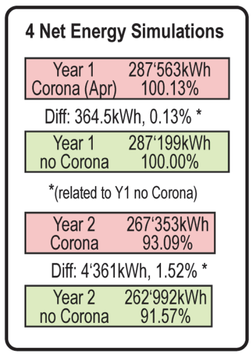

Fig. 16: Simulations

8 Supplementary study

When submitting this project, the FOT wanted an additional study to find from the metro project general requirements for energy-efficient vehicles and a simplified measurement plus data evaluation for existing or new vehicles. In the course of the project, it turned out that this additional study could be elaborated less from the complex metro project (with a quite simple vehicle in terms of HVAC energy) than from more general considerations. We have tried to solve the task to the best of our knowledge and can only set general requirements for energy-efficient vehicles and define different simplified measurement systems that allow the most elementary measurements to be made.

8.1 Requirements for energy-efficient vehicles

Requirements:

- Sleep mode for HVAC
- Sleep mode for auxiliaries
- Flexible indoor temperature setpoint depending on the outdoor temperature (To) and no heating and cooling between e.g. To = 17°C - 23°C (ventilation only)
- Increased forced ventilation with outside air if the CO_2 level exceeds about 1'000 ppm
- Measurement-based control of HVAC systems to meet efficiency, comfort / health parameters
- Exhaust air heat exchanger (saves heating energy in winter and cooling energy in summer)
- State-of-the-art insulated vehicle shell and thermally insulated windows (preferably microwave permeable to save repeaters for mobile phones[2])
- If possible, heat and cool with a heat pump (CO_2 coolant)
- Efficient LED lighting with automatic control
- Efficient drive system with recuperation of brake energy into the overhead line
- KERS (Kinetic Energy Recovery System) with supercapacitor stores excess non-recuperable braking energy on bord and helps to accelerate, or with stationary flywheel on the power grid
- Measuring system integrated by the manufacturer to monitor and record the energy consumption of the main consumers (traction, HVAC, auxiliaries) and the internal and external temperature during standby and operation (preferably with remote access to the data)

The order of the requirements roughly corresponds to the feasibility.

A lot of energy can be saved in standby with the sleep mode of the heating and auxiliaries. The adjustable (flexible) interior temperature that depends on the outside temperature could save a lot heating and cooling energy, especially in local traffic. This minimises the temperature difference between the inside and outside temperature and spares passengers (clothed depending on to the weather) a temperature shock when getting on and off the short-distance vehicle.

The CO_2-level dependent ventilation and exhaust air heat exchanger would be ideal in an airtight long-distance train width good insulated walls, thermally better insulated windows and heat pump heating and cooling.

By monitoring CO_2, VOC, temperature, humidity the HVAC system can be controlled to meet efficiency, comfort and health parameters.

Efficient LED lighting and drive systems with regenerative braking into the overhead line should be standard by now.

With electric braking, the motors work as generators and pass on the recovered energy to nearby vehicles via the overhead line. If there are not enough trains in the vicinity, to consume this energy, a part is burnt off in the roof resistors. Therefore, a KERS could temporarily store all the braking energy and use it again during the next acceleration phase.

If energy measurement systems were already installed in the vehicles by the manufacturer, energy-saving measures could be found and checked more easily. For example, a display of consumption in kWh per km could help the driver to drive more energy efficiently. The consumption values of the same route sections could also be stored in the train in order to analyse which driving style saves more and train the drivers accordingly.

[2] Andreas Schüler EPFL: FOT-Project P-034 WindowWave

8.2 Simplified measurement technology and data evaluation

Since public transport vehicles are used in different ways and are usually technically designed completely differently, it is not possible to build a simple universal measuring system for all these vehicles. Above all, the sensors and energy meters to be installed somewhere on the vehicle require a deep understanding of the technical structure of each vehicle, which only the manufacturer has. It is therefore logical that the manufacturer includes the necessary sensors and meters in the design of a new vehicle and integrates them into his on-board control system. In this way, the manufacturer can already access existing sensors and signals and guarantee a high level of operational safety and ease of maintenance. The manufacturer could also record the proposed readings for existing vehicles if the sensors are available on the vehicle and if the recording capacities allow it (number of available inputs, recording time, etc.).

The measurement data should be temporarily stored in the vehicles and periodically saved on an external server with internet access so that the customers have access to the data. CSV is recommended as a simple data format, which can be easily read in. This ensures a high level of data security and makes it easy to view and evaluate the data from any vehicle equipped with a measurement system from any location and over any period of time.

For a sophisticated subsequent evaluation, it is important that additional values such as the time stamp, the vehicle status (operation/standby), the indoor and outdoor temperature (several sensors) are saved with the data. If possible, GPS data (location and speed) and solar radiation sensors on each side parallel to the windows are also recommended.

Where can costs be saved? Since a manufacturer builds many identical vehicles, the high development costs of an integrated measurement system are spread over the number of vehicles and minimise the additional costs. The operator of the vehicles must pay for the server costs of the stored measurement data. Thanks to his many measured vehicles, the operator can certainly negotiate a more favourable price. Manual evaluations to find energy-saving measures will, according to experience, cause by far the greatest costs. Again, the cost of evaluating of one vehicle is reduced by the energy savings on many vehicles. Fully automatic evaluations could save the most money, but unfortunately they are also very difficult to programme. Artificial intelligence would be required for these algorithms, for example to eliminate erroneous measurements or to filter out correlations from highly noisy data.

In order to save costs, the measuring system can of course be simplified. This simplifies the evaluation, but also reduces the benefit. Therefore, three measuring systems with increasing complexity are presented here, including the list of data points to be measured. The measurement of the recuperated energy is kept simple and can be extended if necessary (by internal consumption and braking resistor):

Minimum system with local energy counters, with or without radio data transmission to external server:

- Gross energy (gross)
- Recuperated energy into the overhead line (rec)
- Net energy (by calculation: net = gross – rec)
- Gross traction energy (gross trac)
- Net traction energy (by calculation: net = gross trac – rec)
- HVAC energy of all components together (HVAC)
- Auxiliary energy (by calculation: Aux = net - HVAC)

In the best case, this system requires 4 AC energy meters (16.7 Hz) and smart wiring. If other (internal or external) supply voltages (230V/50 Hz AC, 36 V DC, 1'000 V DC) are used, additional AC meters or complex DC meters with current and voltage sensors (Energy = time integral of the instantaneous values current x voltage) are used, which then have to be added up to the desired final energies. This makes even the simplest measuring system quite complex. The data should be stored at least as a daily average.

Only simple evaluations are possible, such as the energy breakdown of the net energy into the 3 main groups, or how much energy could be recuperated (daily or larger time periods). This at least gives a rough overview and enables a comparison with the same vehicles with similar workload on the same route.

Medium system with breakdown of HVAC values and radio data transmission to external server

- Gross energy (gross)
- Recuperated energy into the overhead line (rec)
- Net energy (by calculation: net = gross – rec)
- Gross traction energy (gross trac)
- Net traction energy (by calculation: net = gross trac – rec)
- HVAC energy of all components together (HVAC)
- Heating energy (part of HVAC)
- Ventilation energy (part of HVAC)
- Cooling energy (part of HVAC)
- Auxiliary energy (by calculation: Aux = net - HVAC)
- 2 shaded outside and some inside temperature/ humidity sensors (1 for each climate zone)
- Vehicle status bit (1 = operating, 0 = standby)

In addition to the minimum system, the HVAC values are measured and stored individually. There is the climate measurement inside and outside (possibly also humidity measurement) and the vehicle status bit. The vehicle status can be used to determine which part of each energy was consumed during operation or standstill. The data should be stored at least as an hourly average (or 15 minutes).

Here, more detailed evaluations are possible, especially for the HVAC values. Thanks to the temperature sensors, informative specific heating or cooling power curves can be created during operation or standby. For example, the U-value of the envelope can be easily determined under real conditions at standstill and in operation - simply divide the slope of the trend of the respective specific heating power curve (in [W/°C]) by the surface area of the vehicle (in [m^2]). See also appendix A10.

Maximum system with GPS, solar sensors and radio data transmission to external server

- Gross energy (gross)
- Recuperated energy into the overhead line (rec)
- Net energy (by calculation: net = gross – rec)
- Gross traction energy (gross trac)
- Net traction energy (by calculation: net = gross trac – rec)
- HVAC energy of all components together (HVAC)
- Heating energy (part of HVAC)
- Ventilation energy (part of HVAC)
- Cooling energy (part of HVAC)
- Auxiliary energy (by calculation: Aux = net - HVAC)
- 2 shaded outside and some inside temperature / humidity sensors (1 for each climate zone)
- Vehicle mode bit (1 = operating, 0 = standby)
- GPS sensor for speed, track coordinates and distance travelled
- 2 solar radiation sensors, one on each side parallel to the windows
- CO_2 sensors (1 for each zone, air quality and passenger occupancy indicator)

In addition to the medium system GPS-data, temperatures, solar radiation and CO2-level are measured. This additional data allows much better evaluations. With the measurement of solar radiation, the influence of the sun on the heating or cooling behaviour can be studied or calculated away. The GPS values are particularly valuable for evaluating traction and also show the position. From energy differences (e.g. every 5 min) it is very easy to calculate average power values which are important for time diagrams and simulations. The data should be stored at least each minute (as average values).

The maximum system corresponds approximately to the measuring system used in this project. The detailed measurements contain hidden data that can be extracted with a little imagination and appropriate effort. Only with this system was it possible to determine the energy improvements of the vehicle from the first year of measurement to the second year of measurement despite many interfering factors (climate, operating time, operating distance, solar heating and corona door opening measurements).

Although such measurement systems are conceivable for all types of public transport vehicles, there are types that are less suitable:

- Vehicles with combustion engines (diesel buses, diesel ships -> difficult measurement)
- Locomotives (the total energy of a train is already increasingly measured for cost accounting)
- Single carriages in different compositions (no traction values for comparison)
- Funiculars, cable cars

9 Energy consumption of different vehicles for passenger transport

Here is a comparison of different vehicles and their energy consumption per 100 passenger kilometres. Such comparisons are difficult to make and the results should always be critically questioned. Part of the data comes from vehicles measured by the University of Basel, the tram from the 2019 annual report of the Geneva Public Transport Company TPG (marked in blue) and the rest from the public Mobitool V2.1 list. Some of the Mobitool data sets had to be interpolated to fit our vehicles.

Vehicle, Company	Type	Drive	Energy/100km	Passengers		Occupancy		Energy/100 passenger km		Grey Energy/100 passenger km (normal occupation)	
			vehicle		4p/m2		Mobi Tool	full occupation	normal occupation	Grey Energy	Total Energy
			[kWh/100km]	seats	standing	100%	normal	[kWh/100pkm]	[kWh/100pkm]	[kWh/100pkm]	[kWh/100pkm]
E-Bike	E-Bike	electric	1.0	1	0.0	1	100.0%	1.0	1.0	8.1	9.1
Motorscooter electric	Motorscooter electric	electric	3.0	2	0.0	2	66.7%	1.5	2.2	18.2	20.4
FLIRT, SOB	Local train	electric	558.8	217	243.0	460	26.2%	1.2	4.6	4.7	9.4
NINA, BLS	Local train	electric	381.5	150	140.0	290	26.2%	1.3	5.0	5.0	10.0
ICN, SBB	Long-distance train	electric	974.6	470	0.0	470	32.6%	2.1	6.4	5.4	11.7
Tram TPG	Tram (average Geneva)	electric	280.0	66.5	176.8	243	15.9%	1.2	7.3	22.3	29.5
Trolleybus ST4, tl	City trolleybus	electric	222.5	50	60.0	110	19.0%	2.0	10.6	23.5	34.1
Metro m1, tl	Metro m1 Lausanne	electric	371.0	92	91.3	183	17.3%	2.0	11.7	22.2	33.9
Electric car average	Electric car average	electric	20.0	5	0.0	5	32.0%	4.0	12.5	63.2	75.7
Intercity bus	Intercity bus (Coach)	diesel	332.0	50	0.0	50	42.0%	6.6	15.8	10.1	25.9
Motorscooter	Motorscooter	petrol	29.8	2	0.0	2	66.7%	14.9	22.3	13.4	35.7
Motorbike average	Motorbike average	petrol	45.6	2	0.0	2	66.7%	22.8	34.2	33.7	67.9
Car average (diesel)	Car average (diesel)	diesel	60.4	5	0.0	5	32.0%	12.1	37.8	46.8	84.6
City bus average	City bus average	diesel	422.8	60	0.0	60	17.0%	7.0	41.5	21.4	62.8
Car average (petrol)	Car average (petrol)	petrol	75.2	5	0.0	5	32.0%	15.0	47.0	48.8	95.8

Fig. 17 Vehicle comparison table

All values are averages over one year. The energy values of the vehicles for 100 km are complete and include consumption for drive, heating, air conditioning, auxiliary consumers and standby consumption. Very important is the maximum passenger capacity (seating and standing) and the occupancy rate, so that the energy per passenger and 100 km can be calculated.

Diesel and petrol consumption can be converted into kWh using the corresponding calorific values (9.8 kWh/l, 8.5 kWh/l. Likewise, mega joules can be easily converted into kWh (1 kWh = 3.6 MJ).

This list is sorted by the column of energy consumption per 100 passenger-kilometres (marked in red) with normal occupancy (see Fig. 18).

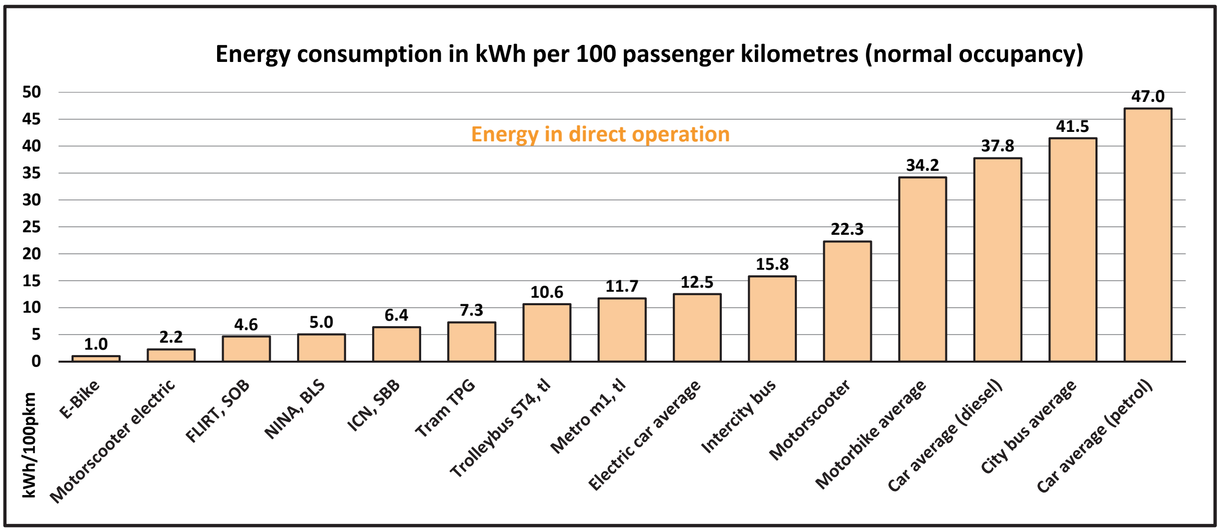

Fig. 18 Vehicle comparison diagram – direct energy consumption per passenger per 100 km

In principle, electrically powered vehicles require less energy per 100 passenger kilometres than thermally powered vehicles due to their better efficiency. If the measured occupancy rates of about 17 % for the metro in Lausanne and the trams in Geneva were also valid for the local trains (Flirt, Nina, 26 %) and the long-distance train (ICN, 33 %), their consumption values per 100 passenger kilometres would also be higher.

An electrically powered car with an average of 1.6 passengers can only just keep up. The most efficient vehicle is the muscle-powered bicycle, whose passenger would have to pedal about 0.5 kWh for 100 km (100 W during 5 hours at 20 km/h on level ground).

All electrically powered public transport is very energy efficient. The energy consumption of the aging Metro m1 is about 1.6 times higher compared to modern trams, but still 3.5 times lower than that of a diesel-powered city bus.

Thanks to the Mobitool factors, the grey energy per 100 passenger kilometres can also be determined. Because the data basis of Mobitool is somewhat unclear, the following data must be taken with caution and regarded as approximate values.

Grey energy is consumed to provide the following 4 categories:

- Energy generation and transport used indirectly for operation (“well to tank”)
- Vehicle maintenance
- Vehicle production and disposal
- Track, road or railway (driveway)

The following list shows in detail how the grey energy is composed for the selected vehicles.

Vehicle, Company	Type	Drive	Energy/100 passenger km		Grey Energy/100 passenger km (normal occupation)					Total Energy
			full occupation	normal occupation	Energy generation	Maintenance	Production/disposal	Driveway	Total grey En.	normal + grey
			[kWh/100pkm]	[kWh/100pkm]	[kWh/100pkm]	[kWh/100pkm]	[kWh/100pkm]	[kWh/100pkm]	[kWh/100pkm]	[kWh/100pkm]
E-Bike	E-Bike	electric	1.0	**1.0**	**1.7**	**0.6**	**5.4**	**0.4**	**8.1**	**9.1**
FLIRT, SOB	Local train	electric	1.2	**4.6**	**1.2**	**0.7**	**0.8**	**2.1**	**4.7**	**9.4**
NINA, BLS	Local train	electric	1.3	**5.0**	**1.3**	**0.7**	**0.8**	**2.2**	**5.0**	**10.0**
ICN, SBB	Long-distance train	electric	2.1	**6.4**	**1.6**	**0.5**	**0.5**	**2.7**	**5.4**	**11.7**
Motorscooter electric	Motorscooter electric	electric	1.5	**2.2**	**3.7**	**2.1**	**11.7**	**0.7**	**18.2**	**20.4**
Intercity bus	Intercity bus (Coach)	diesel	6.6	**15.8**	**4.4**	**1.3**	**0.9**	**3.5**	**10.1**	**25.9**
Tram TPG	Tram (average Geneva)	electric	1.2	**7.3**	**11.0**	**1.2**	**0.6**	**9.5**	**22.3**	**29.5**
Metro m1, tl	Metro	electric	2.0	**11.7**	**17.7**	**1.3**	**0.6**	**2.5**	**22.2**	**33.9**
Trolleybus ST4, tl	City trolleybus	electric	2.0	**10.6**	**16.1**	**1.8**	**1.2**	**4.3**	**23.5**	**34.1**
Motorscooter	Motorscooter	petrol	14.9	**22.3**	**8.0**	**2.1**	**2.7**	**0.6**	**13.4**	**35.7**
City bus average	City bus average	diesel	7.0	**41.5**	**11.5**	**2.3**	**1.6**	**6.0**	**21.4**	**62.8**
Motorbike average	Motorbike average	petrol	22.8	**34.2**	**12.5**	**0.7**	**8.5**	**12.0**	**33.7**	**67.9**
Electric car average	Electric car average	electric	4.0	**12.5**	**20.8**	**3.3**	**25.5**	**13.5**	**63.2**	**75.7**
Car average (diesel)	Car average (diesel)	diesel	12.1	**37.8**	**11.9**	**3.4**	**17.9**	**13.6**	**46.8**	**84.6**
Car average (petrol)	Car average (petrol)	petrol	15.0	**47.0**	**19.4**	**2.8**	**14.8**	**11.8**	**48.8**	**95.8**

Fig. 19 Vehicle comparison table (grey energy in detail)

In the following diagram, the total grey energy is added to the energy for direct operation, and the order of the vehicles is adjusted.

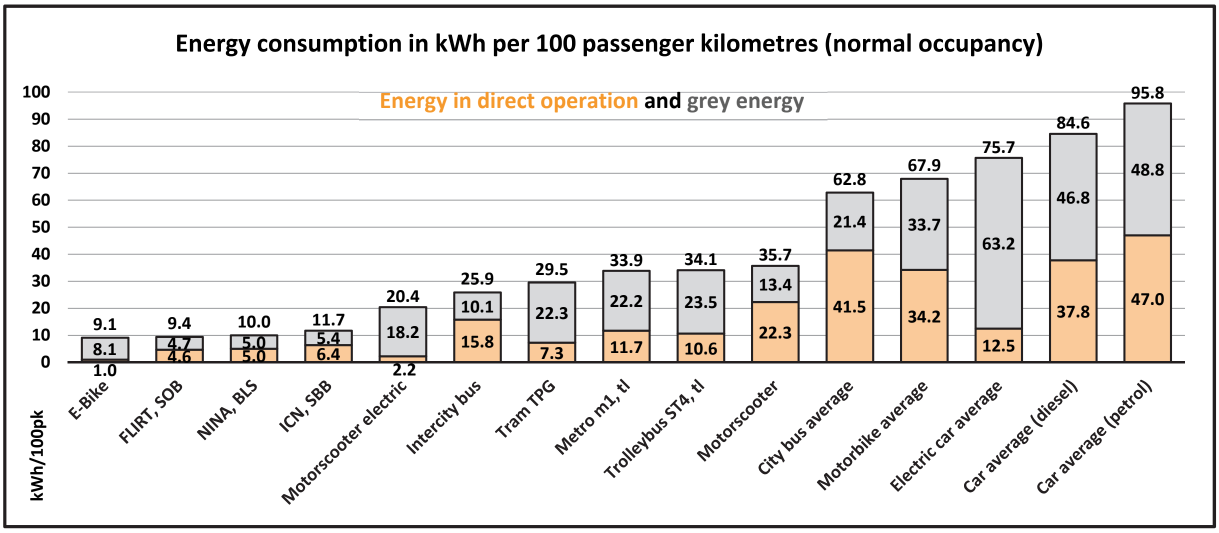

Fig. 20 Vehicle comparison diagram – direct and indirect energy consumption per passenger per 100 km

The local trains Flirt and Nina as well as the long-distance train ICN perform much better in this comparison than tram, metro and trolleybus for the following reasons:

- Higher occupancy rate (from Mobitool) for local and long-distance trains
- Extremely low grey energy for energy generation (SBB network obtains 90% from hydropower)
- Lower grey energy for interurban railways (easier construction and maintenance)

The electric car has the highest grey energy values in practically all categories, which worsens its overall balance enormously. It remains to be seen whether the future battery-powered city buses will not perform similarly badly in terms of the high grey energy. On the other hand, electric vehicles do not emit any pollutants during operation - that is a major advantage.

Including grey energy, the total energy consumption of the Metro m1 compared to the tram is only 1.15 times higher and less than half that of an electric car.

10 Conclusion

Due to the technically complex design of the metro m1, a detailed measuring system was necessary to obtain all the desired data. During the development and installation of the measuring system, several hurdles had to be overcome because the mixture of direct and alternating current systems required innovative solutions. The cooperation of all institutions and companies involved worked out excellently. After the first year of measurements, it became clear that there was still a lot of potential for saving energy in the heating system. As a relatively simple measure, a sleep mode was implemented for the heating system and a slight temperature reduction during operation for the second measurement year. The Corona door opening measures introduced in the last month of the first measurement year to improve ventilation led to a noticeable increase in heating energy consumption, which cancelled out part of the savings of the second year of measurement (23 % of HVAC energy 2nd year). Thanks to the versatile long-term measurement data and the complex evaluation, it was possible to include the Corona door opening measures in addition to the solar radiation and the outside temperature curve in order to compensate for them when comparing the heating energy of the two measurement years.

With simple but effective energy saving measures, more than half of the HVAC energy (56.5 % = 24'206 kWh) could be saved in the 2nd year of measurement, which corresponds to a net energy reduction of 8.43 %. This more than doubled the energy savings of 10,000 kWh per year hoped for when the project was submitted. The measures have already been implemented in all 22 m1 vehicles, resulting in an expected annual saving of 484 MWh (2 vehicles out of 22 are always in reserve).

Possible requirements for the procurement of new energy-efficient rolling stock were compiled in the supplementary project chapter 8.1. The supplementary project also shows a way in which future rolling stock could be ordered with a simple measuring system. With the integrated measuring system, energy efficiency can be continuously monitored and improved through appropriate measures. Excellent and verifiable energy efficiency could be an additional criterion for the purchase of new vehicles.

In chapter 9, the energy consumption of different passenger transport vehicles was compared and it was concluded that public transport is well positioned in terms of energy efficiency.

Fig. 21: m1 in double composition at the EPFL station (photo AT University of Basel)

END of the final report

11 Appendix (a collection of supplementary information)

A1 Power consumption time diagrams during standby (auxiliaries, first year)

The auxiliary units are powered by the static converter, which generates 24 V DC and 230 V 50 Hz AC from the 750 V DC overhead line voltage. During the year, only a small part of the static converter's power is used for cooling, ventilation and the air compressor. As long as the static converter is fed by the overhead line, its loss is a constant 1.3 kW (input power minus output power). In this time diagram, the behaviour of the static converter during one day can be examined.

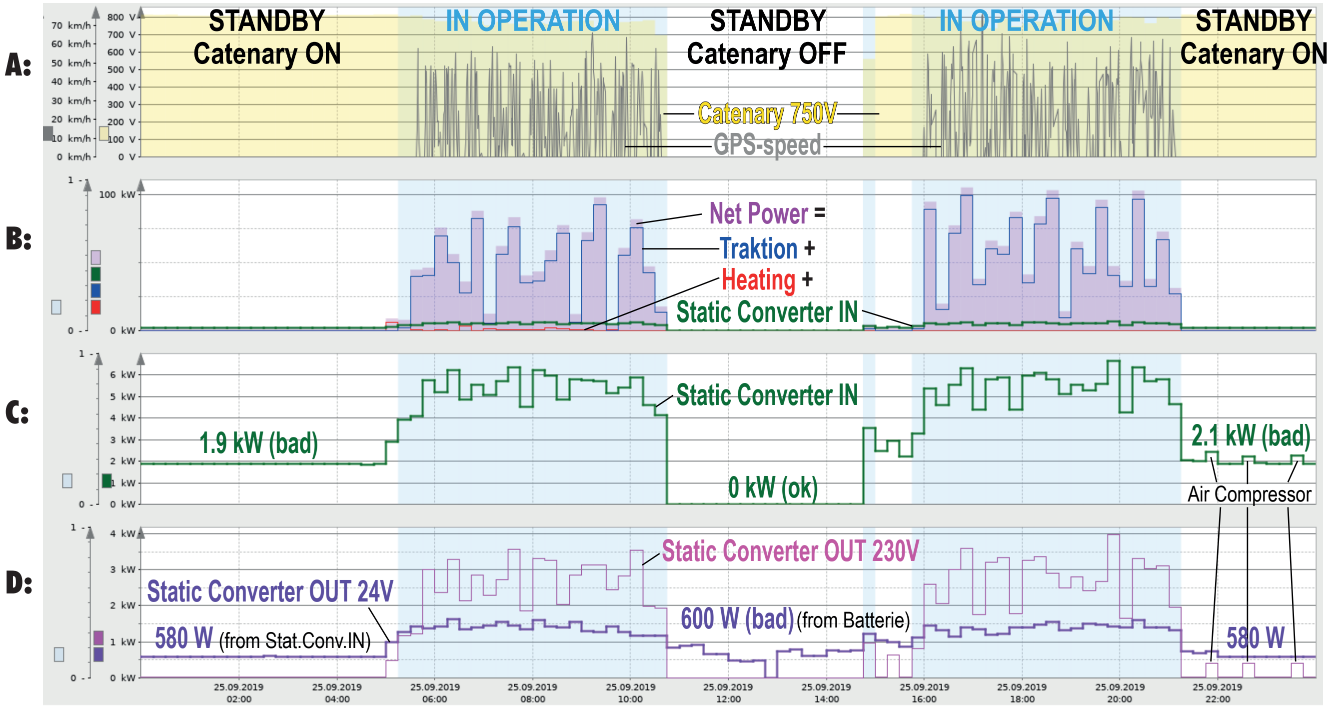

Fig. A1: Time-diagram for one day: Power consumption of auxiliaries during standby (15 minutes averaged intervals)

The above diagram is divided into 4 diagrams labelled A to D, showing the following information and signals:

A: Status: Standby/Operation (blue area), Catenary On (yellow area)/Off and GPS speed.
- normally the catenary is always connected to the overhead line and only off for maintenance work (here 11:00-14:00).

B: Net power, traction power, heating power and static converter input power (mostly auxiliaries) in relation to each other.
- Net power is the sum of net traction, heating and static converter input.

C: Static converter input power (mostly auxiliaries) - enlarged:
- during standby the static converter consumes about 2 kW unless the catenary is off.
- during operation the static converter consumes about 5-6 kW - this increase is mostly due to the air compressor.

D: Static converter outputs 230 V AC (air compressor, cooling of the cabins, fans of the fan heaters) and 24 V DC:
- when the catenary is switched off, there is no 230 V AC present for the air compressor and 24 V is provided by the battery only.
- when the catenary is on, 230 V is used during standby from time to time for the air compressor and 24 V for various consumers.
- these 580 W of the static converter 24 V output during standby is used by various controls (door controller, heating controller etc.)

Without switching off the catenary in park position, the static converter consumes about 2 kW during standby.

A radical idea would be to switch of the catenary and most internal 24 V battery circuits during standby and outside temperatures above 5°C. Most battery consumers have to be switched off too together with the catenary, otherwise the battery load is about 580 to 600 W. The doors should still be active even with pure battery power. Also the DPUB measuring system must stay on.

Unfortunately, for technical reasons, it is not possible to completely switch off the auxiliary units in standby. It would be desirable if tl could at least implement a sleep mode for the auxiliary units so that the standby energy of the auxiliary units could be reduced somewhat.

A2 Power consumption time diagrams during standby (HVAC, first year)

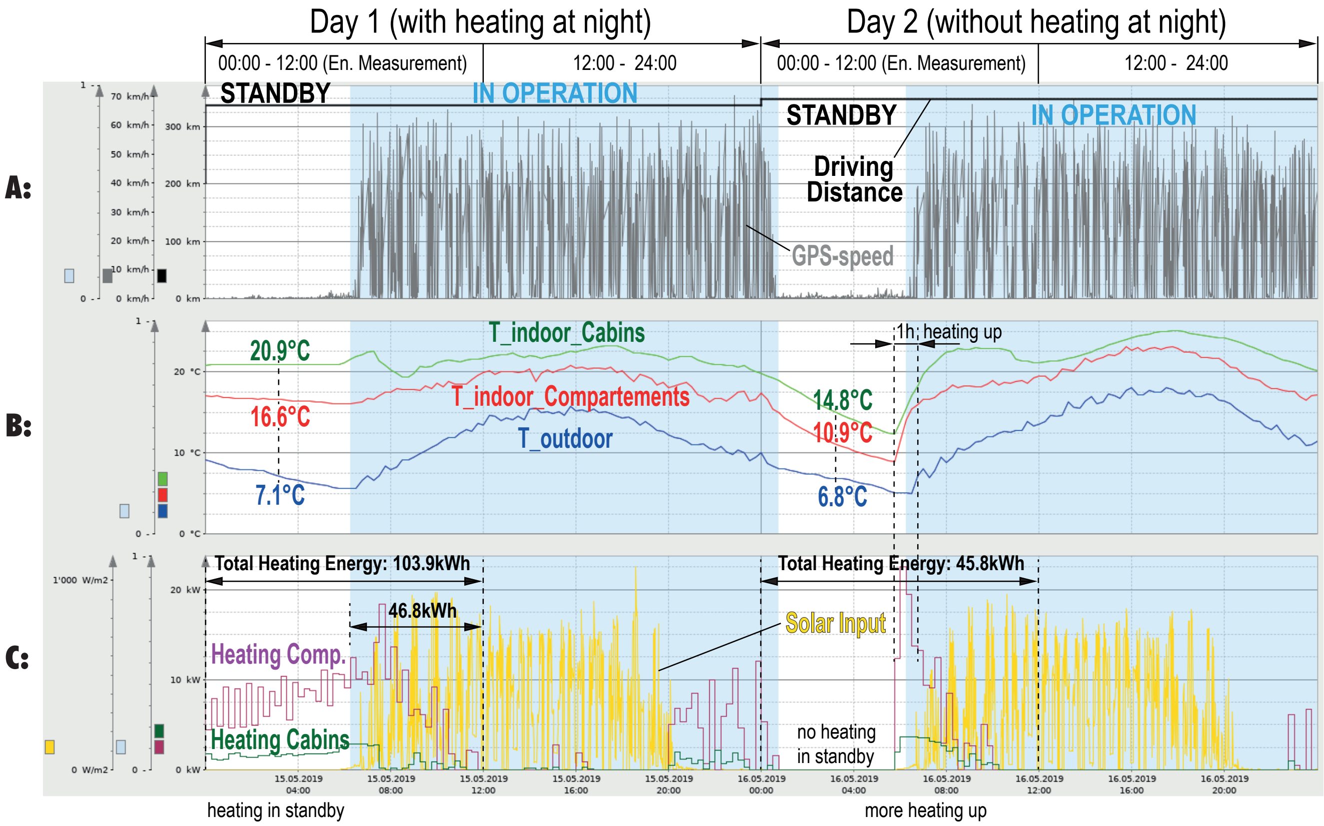

Fig. A2: Comparison of 2 similar nights with or without heating (15 minutes averaged intervals for status and heating power)

The above diagram is divided into 3 charts named A to C and the following information and signals are shown:

A: Status: Standby/Operation (blue area) and GPS speed.

- both days have the same timetable and the operation and standby times are almost identical.

B: Indoor temperature cabins (green), compartments (red) and outdoor temperature (blue).

- the outdoor temperature curves of both days from 00:00 to 12:00 are nearly the same.
- the indoor temperature during the first night is almost constant and 20.9°C in the cabins and 16.6°C in the compartments.

C: Heating power of compartments (violet) and of cabins (green), solar input (yellow, on both days likewise).

- first night: heating on; second night: heating off. During the second night about 58.1 kWh have been saved.

Currently, the metro does not have a sleep mode with a standby temperature reduction. During the transitional period, there may be a night of full heating and rarely the heating is completely switched off overnight. During the colder periods, the compartments are always fully heated and the internal temperature is usually around 18°C and the driver's cab 21°C, even in standby mode (see pages A5 and A7 below).

Coincidentally, 2 very similar days were found where the temperature curve of the outside temperature from 00:00 to 12:00 (half day) looks almost the same. The operating times and the solar radiation are almost identical, but one time the train is heated at night and the other time it is not. Despite the heating-up process and slightly worse conditions, only 44 % of the heating energy is consumed on the second half-day without heating as on the first half-day with full heating. Since the energy consumption of the second half-day (45.8 kWh) is even less than that of the first day from 06:00 to 12:00 (46.8 kWh), the heating-up process in this example did not consume more energy. Because the heating often runs on non-operating days, a lot of energy could be saved with an automatic temperature reduction in standby mode. The minimum indoor temperature could be kept between 5°C and 12°C, for example.

To reduce heating energy consumption in standby, tl should use a sleep mode to lower the heating temperature setpoint to a minimum.

A3 - A9 Getting hidden data out of specific heating power curves (first year)

The specific heating power curve is a graph where the heating power is shown in function of the temperature difference (inside minus outside). The bigger this temperature difference gets, the colder it gets outside and the heating power will rise accordingly to maintain the interior temperature. Only data points with a heating power greater than zero can be used for that curve.

For the specific heating power curve of the metro we took hourly mean values of the total heating power, the temperature difference and many more side data (like standby/operation-mode information, solar radiation, door openings, number of passengers and CO2-concentration). Due to these various side effects there is always a cloud of data points in such a graph through which a linear interpolated straight line can be laid.

Various influences can change the steepness and the offset of the specific heating power curve. These influences can be detected and quantified by clever choosing of data points (e.g. during standby only) or sorting data points in groups each with its own interpolated line (e.g. more sun, less sun). Because of this procedure we can manage the strong influence of the temperature difference and still see other smaller influences.

For these first considerations, the metro was treated as one climate zone and the heating power of compartments and cabs was added.
On the following pages we try to get to the hidden data in these curves step by step.

A3 Comparison of specific heating power curves in standby and in operation

Over 3'000 hourly data points with heating active have been chosen during standby and operation. Both curves differ strongly:

- In standby the heating starts when the outer temperature drops 1.86°C below the inner temperature and the heating power rises gently when it gets colder (1.0948 kW/°C).
- In operation the heating starts when the outer temperature drops 4.28°C below the inner temperature and the heating power rises 1.8 times steeper than the standby curve (1.9661 kW/°C).

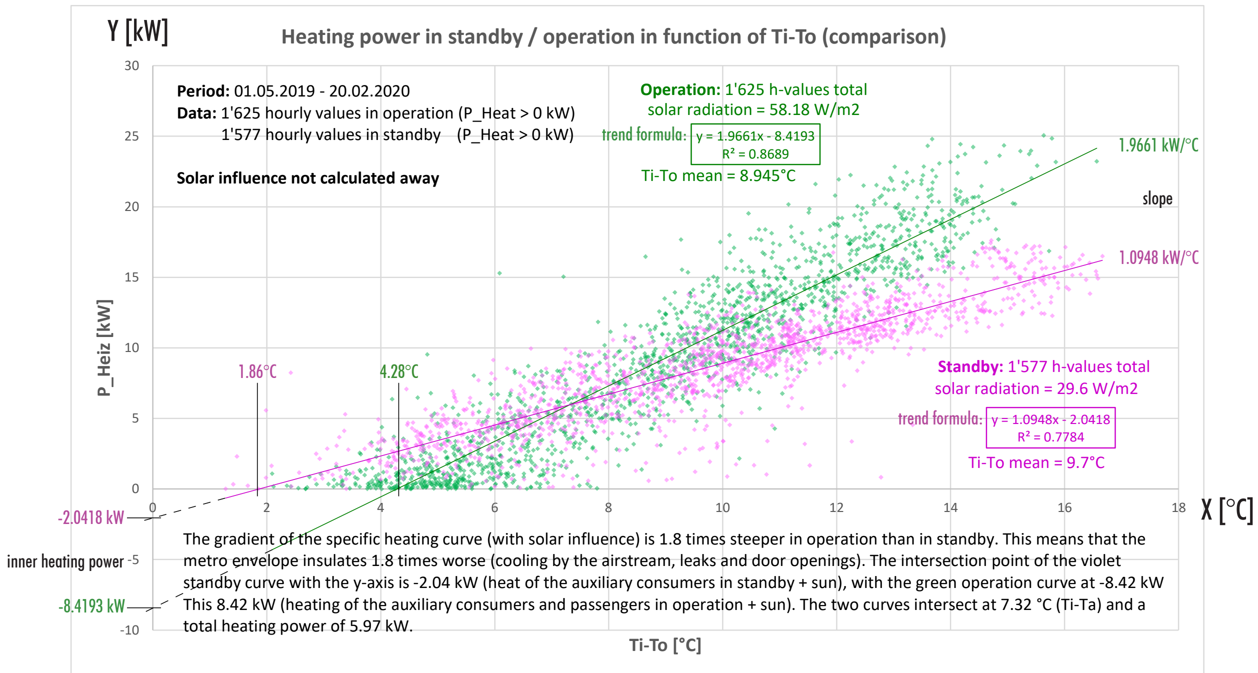

Fig. A3: Comparison of the heating power in standby and operation in function of inside minus outside temperature

Basically the intersection of both interpolated trend lines with the power axis (Ti-To = 0) corresponds with the „inner heating power" from other heating sources than the normal electrical heating that helps heating (therefore the minus values). Without these extra heating sources like sun, auxiliaries and passengers - all heating curves would start at zero temperature difference and zero power.

The steepness of the slope corresponds with the thermal insulation of the metro envelope - the flatter the better the insulation.

The necessary heating power in kW (y) at a certain temperature difference in °C (x) can be easily calculated with the trend formulas. Just put the temperature difference in place of x and calculate the formula. Negative heating power result in zero, heating power above 30 kW become 30 kW (maximum heat output of compartments and driver's cabs).

A4 Specific heating power curves in standby with solar influence

In standby mode, the heating behaviour is only influenced by the temperature difference (inside minus outside), the waste heat of the auxiliary units and the heating by the sun. If the corresponding measuring points are sorted into 2 groups with and without solar radiation, 2 offset trend lines are obtained in the specific heating diagram. The sum of both groups corresponds to the third group of all measurements (black line).

Through a special calculation using the solar radiation values, the influence of the sun can be calculated (see text in the two diagrams below).

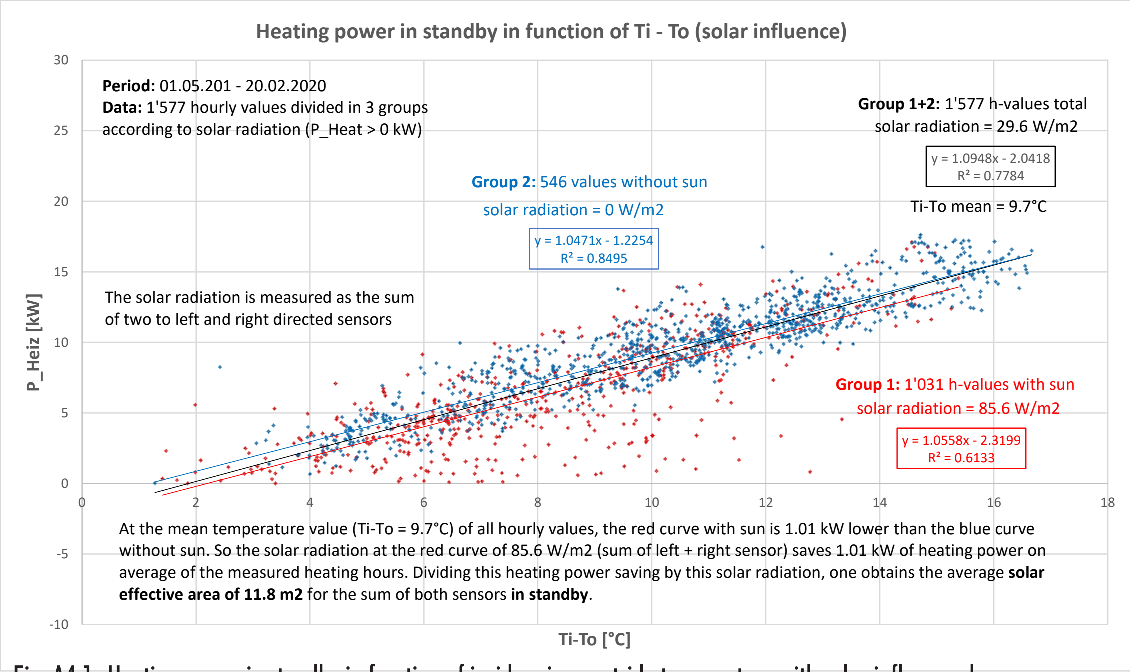

Fig. A4.1: Heating power in standby in function of inside minus outside temperature with solar influence shown

- The solar radiation with its warming effect shifts the heating power curve down by 1.01 kW (group 2 to group 1 at Ti-To=9.7°C)

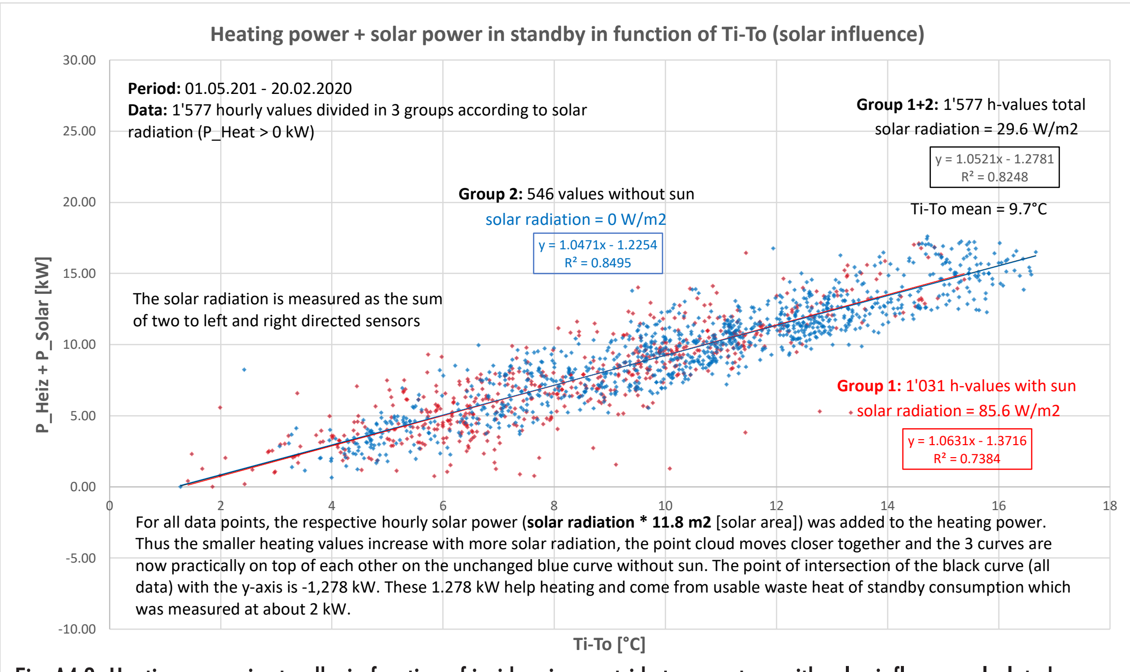

Fig. A4.2: Heating power in standby in function of inside minus outside temperature with solar influence calculated away

- The solar radiation is perfectly calculated away and validates the procedure. See that the red point-cloud moves closer together! With this method, the influence of the sun can be compensated and the resulting average heating power saving can be calculated.

Continuation of point A4 Specific heating power curves in standby with solar influence

Now we can calculate the power values of all parts that help to heat the metro in standby mode at an average temperature of 9.705°C (Ti-To):

P_Heat = 1.0948 kW/°C * 9.705°C - 2.0418 KW = 8.58 kW (Fig. A4.1, equation Group 1+2)

P_Heat + P_Solar = 1.0521 kW/°C * 9.705°C - 1.2781 kW = 8.93 kW (Fig. A4.2 equation Group 1+2)

P_Solar = (P_Heat + P_Solar) - P_Heat = 8.93 kW - 8.58 kW = 0.35 kW

P_Heat_Aux = 1.2781 kW (Fig. A4.2, equation Group 1+2, last part)

P_Heat_Total = P_Heat + P_Solar + P_Heat_Aux = 8.58 kW + 0.35 kW + 1.28 kW = 10.21 kW

A5 Heating power balance in standby (from the above calculations of the specific heating power curves)

Measuring conditions in standby (power values at Ti-To = 9.705°C)

Period:	01.05.2019 - 20.02.2020	1'577 averaged hours	
P_Heat:	>0 kW (for each hour)	Passengers: 0	Doors open: 0%
Solar radiation:	29.639 W/m2	A_Solar: 11.8 m2	
Average temperatures.	17.15°C (indoor)	7.445°C (outdoor)	-> Ti-To = 9.705°C

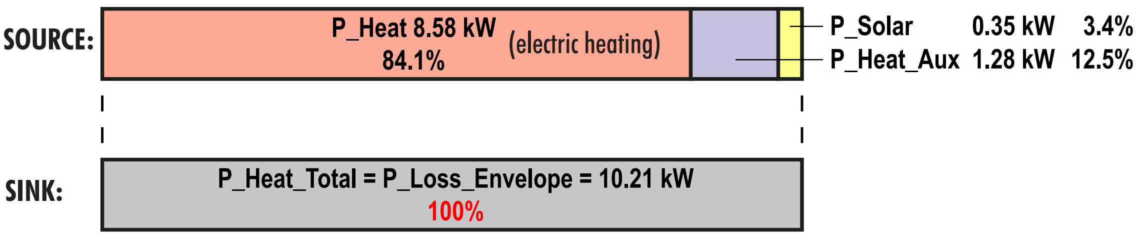

Fig. A5: Heating power balance in standby (shows the average power distribution of all heat sources and the vehicle envelope as heat sink)

During standby operation, a lot of electrical heating energy is wasted, as the interior temperature is kept constant at 17°C in the compartments and 21°C in the cabins by the electrical heaters and with the support of the „waste heat" of the auxiliary units and the heating by the sun through the windows.

The averaged interior temperature results from area-weighted sensors: Compartment = 90.4 %, cabins = 9.6 %.

A sleep mode would let the interior temperature (inclusive cabins) fall down to a minimal temperature (Ti_min) and stabilise it there.
This has been simulated with the heating power formula (Fig. A4.1, equation Group 1+2) for all 1'577 measuring hours:

Ti_min	P_Heat	Saving in standby mode compared to P_Heat = 8.58 kW at Ti=17.15°C as it is now.
5°C	0.204 kW	97.6 %
8°C	1.05 kW	87.8 %
12°C	3.56 kW	58.5 %

A lot of heating energy could be saved with a sleep mode to reduce the heating in standby - even with moderate reductions.

Temperature setpoints in standby	Compartments	Driver's cabins
First measurement year	18°C	21°C
Second measurement year (proposal)	8°C	17°C

The temperature in the driver's cabins in standby is to be lowered less for technical reasons and the shorter heating time.

A6 Specific heating power curves in operation with solar influence

In operating mode, the heating behaviour is influenced by the temperature difference (inside minus outside), the waste heat of the auxiliary units, the heating by the passengers, the door openings, the increased air speed during the journey and the heating by the sun. If the corresponding measuring points are sorted into 2 groups with more and with less solar radiation, 2 offset trend lines are obtained in the specific heating diagram. The sum of both groups corresponds to the third group of all measurements (black line).

Through a special calculation using the solar radiation values, the influence of the sun can be calculated (see text in the two diagrams below).

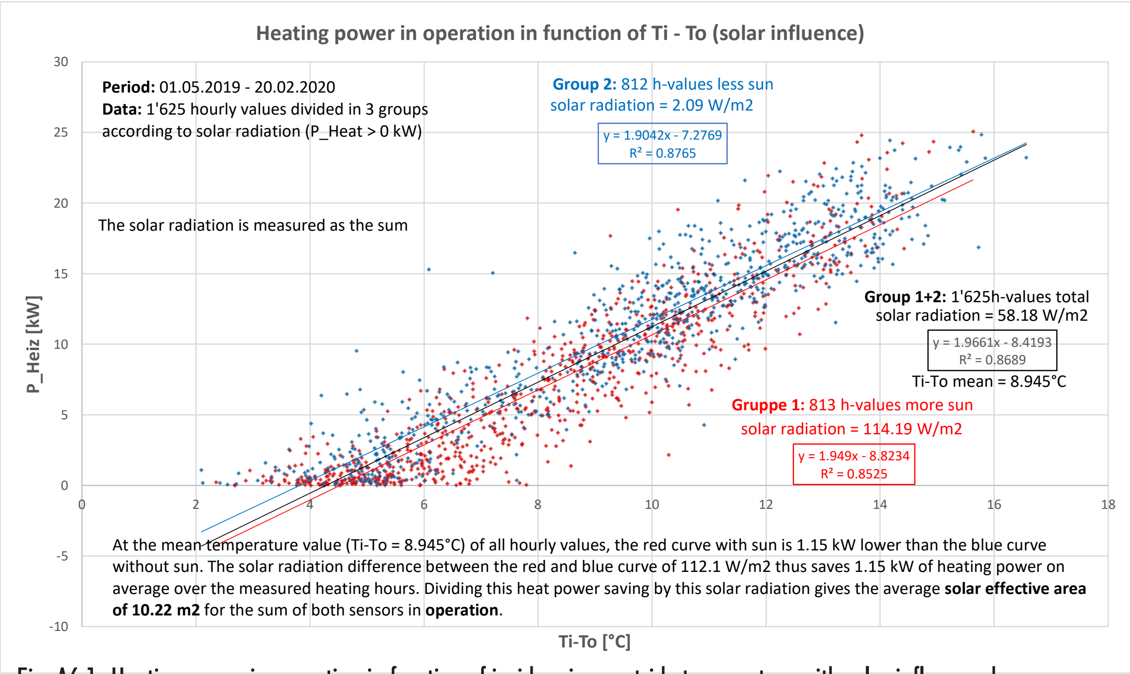

Fig. A6.1: Heating power in operation in function of inside minus outside temperature with solar influence shown

- The solar radiation with its warming effect shifts the heating power curve down by 1.15 kW (group 2 to group 1 at Ti-To=8.945°C)

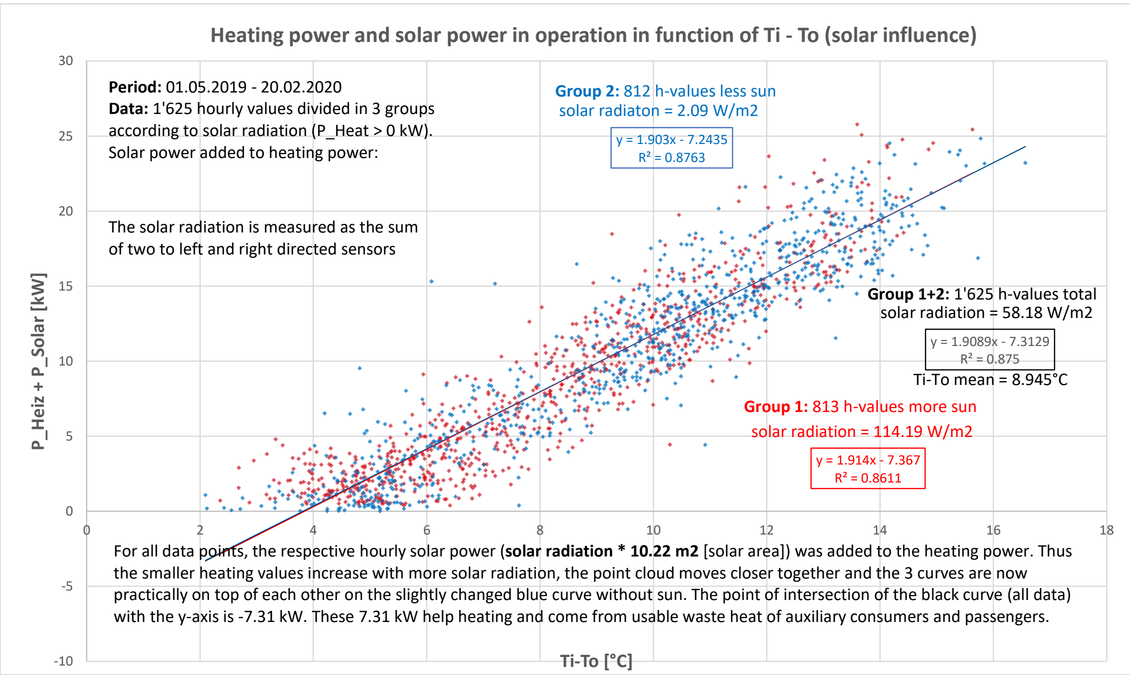

Fig. A6.2: Heating power in operation in function of inside minus outside temperature with solar influence calculated away

- The solar radiation is perfectly calculated away and validates the procedure. See that the red point-cloud moves closer together!
  With this method, the influence of the sun can be compensated and the resulting average heating power saving can be calculated.

Continuation of point A6 Specific heating power curves in operation with solar influence

Now we can calculate the power values of all parts that help to heat the metro in standby mode at an average temperature of 8.945°C (Ti-To):

P_Heat = 1.9661 kW/°C * 8.945°C - 8.4193 KW = 9.17 kW (Fig. A6.1, equation Group 1+2)

P_Heat + P_Solar = 1.9089 kW/°C * 8.945°C - 7.3129 kW = 9.76 kW (Fig. A6.2, equation Group 1+2)

P_Solar = (P_Heat + P_Solar) - P_Heat = 9.76 kW - 9.17 kW = 0.595 kW

P_Heat_Aux + P_Heat_Passengers = 7.3129 kW (Fig. A6.2, equation Group 1+2, last part)

P_Heat_Passengers = 58.7 Pass. * 60 W = 3.52 kW (60 W per Person with clothing) P_Heat_Aux = 7.31 kW - 3.52 kW = 3.79 kW

P_Heat_Total = P_Heat + P_Solar + P_Heat_Aux + P_Heat_Passengers = 9.17 kW + 0.595 kW + 3.79 kW + 3.52 kW = 17.08 kW

A7 Heating power balance in operation (from the above calculations of the specific heating power curves)

Measuring conditions in operation (power values at Ti-To = 8.945°C)

Period:	01.05.2019 - 20.02.2020	1‘625 averaged hours
P_Heat:	>0 kW (for each hour)	Passengers: 58.68 Doors open: 14.1%
Solar radiation:	58.175 W/m2	A_Solar: 10.22 m2
Average temperatures.	17.881°C (indoor)	8.936°C (outdoor) -> Ti-To = 8.945°C

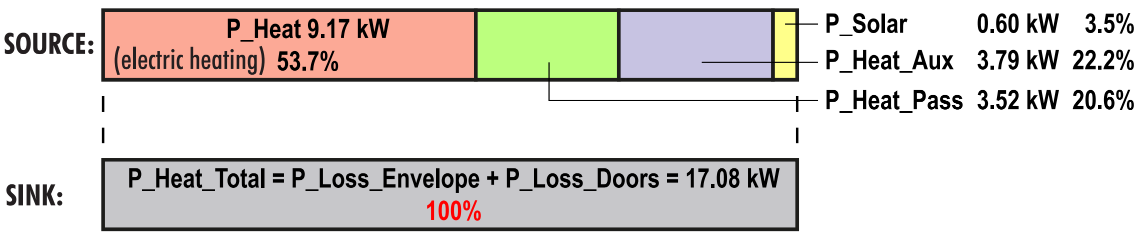

Fig. A7: Heating power balance in operation (the power loss by the doors will be investigated on the next pages)

On average, almost half of the heating power is provided by the passengers, the waste heat from the auxiliary units (including the engines) and the sun. With passengers, the measured compartment temperature increases by about 1°C to 18°C during operation compared to standby.

So during operation, the interior temperature is kept constant at around 18 °C in the compartments and 21 °C in the cabins.
The averaged interior temperature results from area-weighted sensors: Compartments = 90.4 %, Cabins = 9.6 %.
This was simulated with the heating power formula (Fig. A6.1, equation group 1+2) for all 1‘625 measurement hours:

- dTi	P_Heat	Saving in operation mode compared to P_Heat = 9.17 kW (at Ti=17.881°C as it is now)
- 1°C	7.71 kW	19.2 %
- 2°C	5.86 kW	36.1 %
- 3°C	4.49 kW	51.0 %
- 4°C	3.28 kW	64.3 %
- 5°C	2.22 kW	75.8 %

Lowering the setpoint of the interior temperature in operation by 3°C will half the electrical heating power during operation.

Temperature setpoints in operation	Compartments	Driver‘s cabins
First measurement year	18°C	21°C
Second measurement year (proposal)	15°C	21°C

The temperature in the driver‘s cabins can be changed manually by the driver during operation (16°C - 30°C).

A8 Specific heating power curves in operation with door opening influence

The same measured values in operation are now sorted into several groups with door openings of different lengths. The shorter the doors are open, the better the insulation of the envelope and the trend curves become flatter.

From this, the trend curve can be estimated mathematically if all doors were always closed and compared with the measured trend curve in operation. With these two trend curve equations, the influence of the door opening can be calculated.

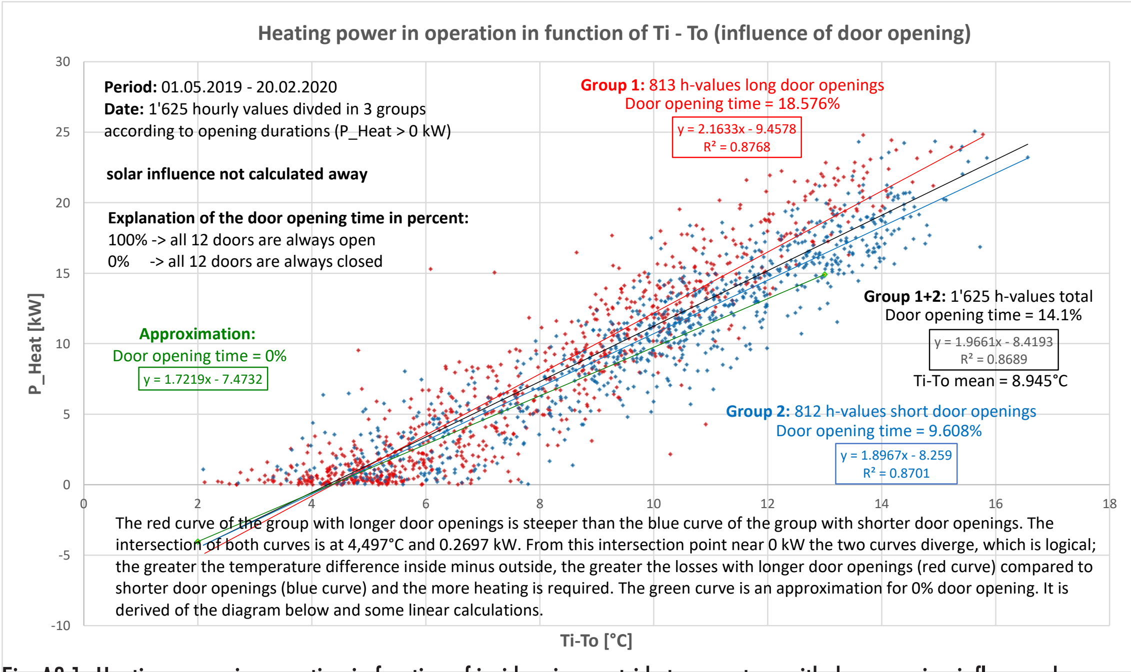

Fig. A8.1: Heating power in operation in function of inside minus outside temperature with door opening influence shown

- Averaged over all data points the electric heating power loss by the door opening is 1.24 kW of 9.17 kW (13.5 % at Ti-To=8.945°C)

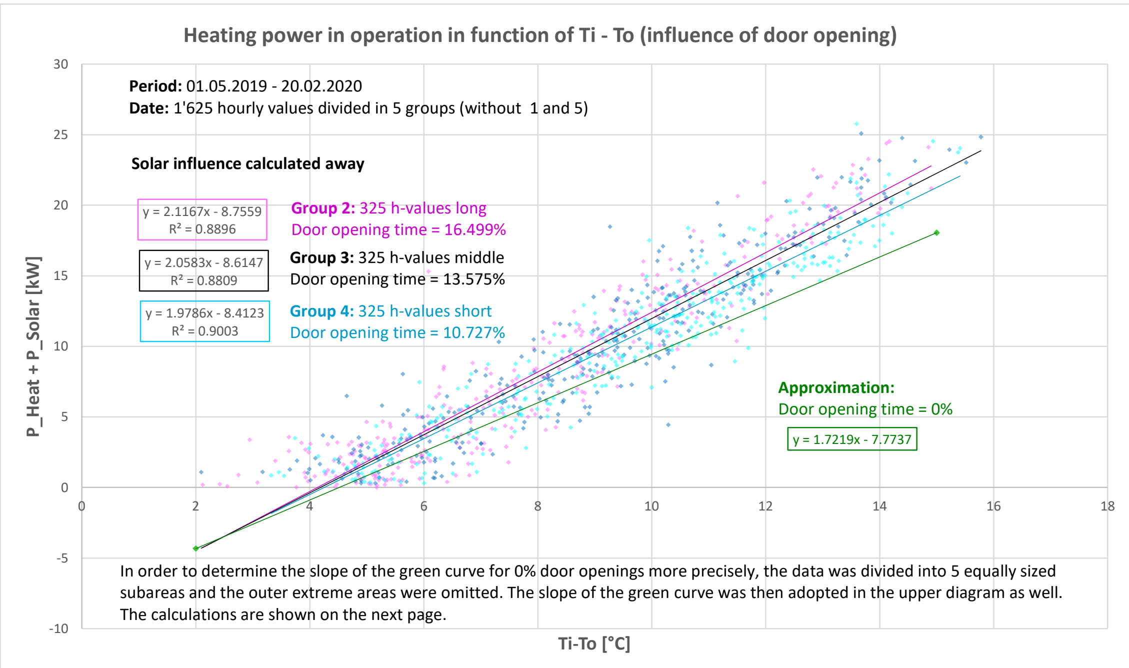

Fig. A8.2: Heating power in operation in function of inside minus outside temperature - determination of the slope for 0 % door opening

- This diagram helped to determine the slope of the curve at 0 % door opening time more precisely (see next page for calculations).

Continuation of point A8 Specific heating power curves in operation with door opening influence

The power values of all parts which helps heating the metro during operation at the mean value of 8.945°C (Ti-To) are the same as on page A7 at the top:
P_Heat = 9.17 kW / P_Heat_Passengers = 3.52 kW / P_Solar = 0.595 kW / P_Heat_Aux = 3.79 kW / P_Heat_Total = 17.08 kW

Calculation of the linear interpolation of the 0% door opening curve:
From the equations in fig. A8.2 of group 2 (16.499 % door opening) and group 4 (10.727 % door open.) the slope for 0 % door open. was calculated:
m = 1.9786 - ((2.1167-1.9786)/(16.499 %-10.727 %)*10.727 %) = 1.7219 (slope for 0 % door opening)
In both diagrams (fig. A8.1 and A8.2) a green line with this slope was laid trough the intersection of the „red" and „blue" lines.

With the formula of fig. A8.1 to calculate the heating power at the mean value of 8.945°C (Ti-To) at 0 % door opening: y=1.7219x - 7.4732
-> P_Heat_Doors_0% = 1.7219 kW/°C * 8.945°C - 7.4732 kW = 7.93 kW

-> P_Loss_Doors_electric = P_Heat - P_Heat_Doors_0% = 9.17 kW - 7.93 kW = 1.24 kW (13.5 % of P_Heat, „measured")
-> P_Loss_Doors = P_Loss_Doors_electric * P_Heat_Total / P_Heat = 2.31 kW (13.5 % of P_total, „upscaled")

A9 Final heating power balance in operation (with door loss) (from the above calculations)

Measuring conditions in operation (power values at Ti-To = 8.945°C)

Period:	01.05.2019 - 20.02.2020	1'625 averaged hours
P_Heat:	>0 kW (for each hour)	Passengers: 58.68 Doors open: 14.1%
Solar radiation:	58.175 W/m2	A_Solar: 10.22 m2
Average temperatures.	17.881°C (indoor)	8.936°C (outdoor) -> Ti-To = 8.945°C

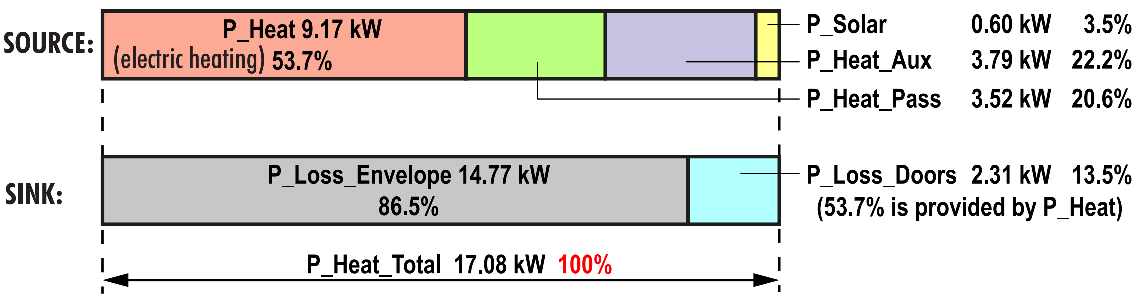

Fig. A9: Final heat output balance during operation including the power loss through the doors

In average almost half of the heating power is provided by the passengers, the waste heat of auxiliaries (including motors) and the sun.
The energy loss by the doors is about 1.5 times over compensated by the passengers. P_Heat provides only 1.24 kW for the door power loss.
Let's look at what shorter door opening would save in a proportional calculation.

Door Open	Reduction	P_Loss_Doors_electric	Saving of P_Heat (9.17 kW = 100%)
14.1 %	0 %	1.24 kW	0 %
12.7 %	-10 %	1.11 kW	1.42 %
11.3 %	-20 %	0.991 kW	2.72 %
7.05 %	-50 %	0.619 kW	6.75 %

There is no big gain to shorten the door openings (only 0.11 % of the net energy over the year by 10 % reducing of the door opening times).
Better insulation of the metro could save a bigger part of the heating energy, but would be complex and expensive (see page A10).
It is amazing what can be read out of the specific heating power curves and some additinal information.
In addition, the U-value of the envelope can be calculated from the slope of the specific heating power curve. (see also page A10).

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A10 Better thermal insulation of the metro envelope (U-value, first year)

It should be investigated whether it would be worthwhile to improve the insulation of the metro. The easiest way would be to replace the existing single-glazed windows with double-glazed thermal insulation windows. Some things are simplified in the following consideration.

An important parameter for thermal insulation is the heat transfer coefficient U in [W/m²K]:

U = P_Heat / A * dT   P_Heat: Heating Power in [W], A: Area in [m²], dT: Temperature Diff. in [K] or [°C]

The U-value of 1 W/m²K for a window of 1 m² means: with a temperature difference of 1 K between both sides, 1 W of heat flows through it.

The smaller the U-value, the better the thermal insulation. Here are some typical examples of U-values in still air:
single glazed window: 5.9 W/m²K   double glazed window: 3.0 W/m²K   heat-insulating window: 1.1 W/m²K   house wall: 0.28 W/m²K

The metro has two U-values - one in standby (still air) and one during operation (added cooling by airstream, leaks and door openings).
Surface area of the metro: A = 302.9 m² (it was calculated as a simple rectangular block).

If you divide the slope of the specific heating power curve in [W/°C] by the surface area of the vehicle in [m2], you also get the U-value.
The slopes result from the formulas in Fig. A3 (page A3): The values of the slopes are given there in kW/°C
Heat transmission coefficient of the metro in standby: U_Standby = (1'094.8 W/°C) / 302.9 m² = 3.61 W/m²K
Heat transmission coefficient of the metro in operation: U_Operation = (1'966.1 W/°C) / 302.9 m² = 6.49 W/m²K

These values are poor. The standby value lies somewhere between a single and double glazed window.
The „real" U-values obtained in this way include all possible external influences that occur primarily during operation. In standby mode without sunlight, they can be better compared with U-values measured in climatic chambers without external influences (sun, doors.

If we replace all window surfaces of the compartments (13.66 % of 302.9 m²) with a good double glazed thermal insulation glass (U-value: 1.1 W/m²K), the new U-value of the envelope would decrease by 18.1 % to 81.9 % of the old U-value (external calculation).

To calculate the effect of 18.1 % better thermal insulation, both slopes in Fig. A3 (for standby and operation) are reduced by 18.1 %. These modified formulas are applied to the measured year and the results can be compared.

These formulas are surprisingly accurate as they also include the values of the metro's internal heat sources. However, they only apply above a minimum temperature at which the values of the power curve become positive. Below this minimum temperature to be calculated, the heating power is always zero.

All electrical heating of the metro is provided by fan heaters. 18.1 % better thermal insulation reduces the slopes of both heating power formulas in fig. A3 by a factor of 0.819:

P_Heat_Standby = 0.819 * 1.0948kW/°C * dT - 2.0418 kW (for dT > 2.277°C, otherwise P_Heat_Standby = 0)

P_Heat_Operation = 0.819 * 1.9661kW/°C * dT - 8.4193 kW (for dT > 5.229°C, otherwise P_Heat_Standby = 0)

In a simulation the input to the formula was the measured temperature difference inside minus outside (dT = Ti - Ta, 15 minute periods) and all outputs were added and converted to obtain the heating energy for 11 month of the first year. To obtain the HVAC energy, the unchanged cooling energy and the simulated energy of the fan heaters were also added.

This measure (P4) would save 11'140 kWh from 267'153 kWh, that is 4.17 % from the overall net energy.

The most sensible combinations of all six proposals (P1 - P6) are shown in a table (Final Report, page 10). Since the energy saving proposals partly overlap, this must be taken into account when calculating the total energy savings.

Together with the easier to implement heating saving measures P2 and P3 (see final report, page 10), better windows (P4) would save 12.21 % of the net energy, which is only 1.82 % more than the 10.39 % that P2 and P3 alone would achieve. At a roughly estimated cost of CHF 50'000 to replace the 26 windows, the payback is 57 years. Retrofitting is therefore not worthwhile for this measure.

A11 Detailed energy consumption of both measuring years (summer, winter)

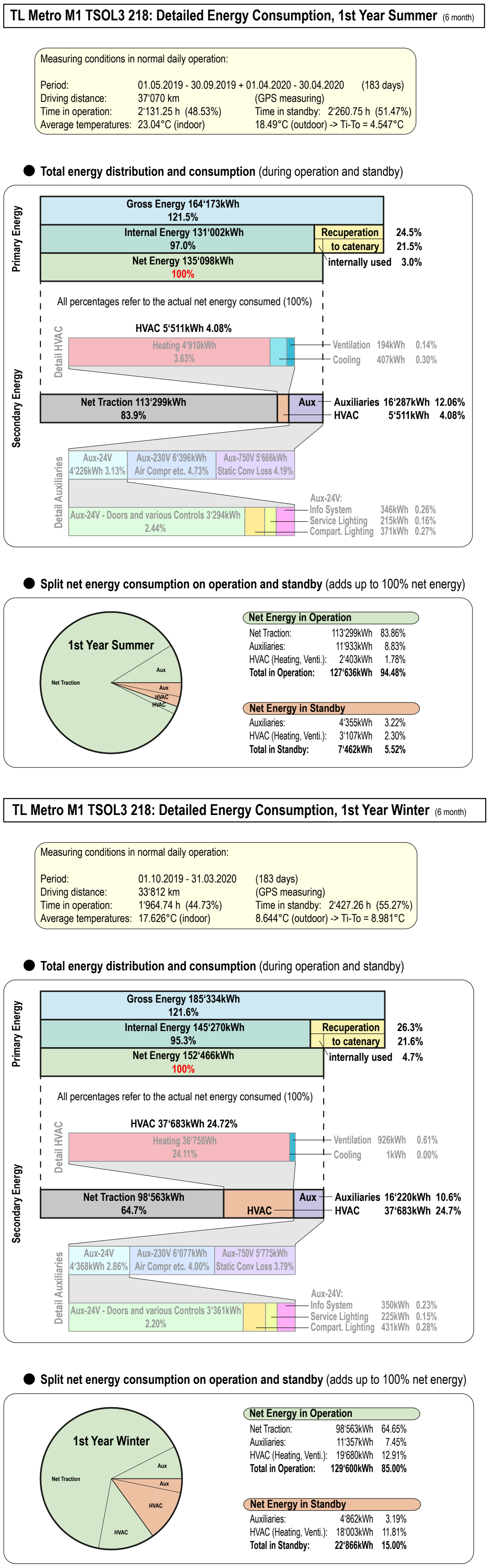


Fig. A11.1: Energy consumption 1st year (summer and winter)

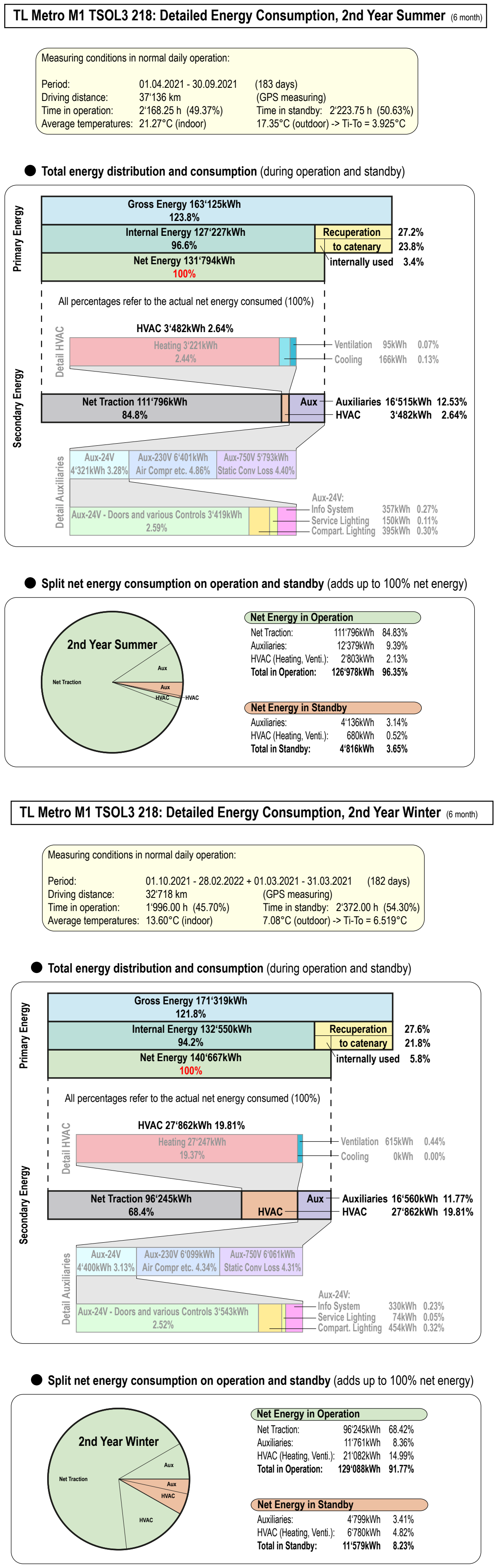


Fig. A11.2: Energy consumption 2nd year (summer and winter)

A12 Detailed energy consumption of both years (total)

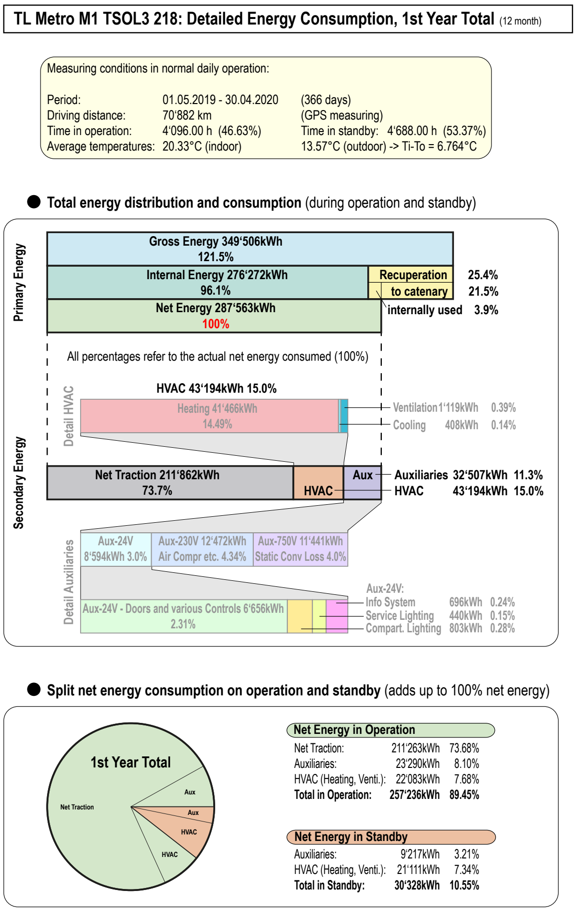


Fig. A12.1: Detailed energy consumption 1st year (total)

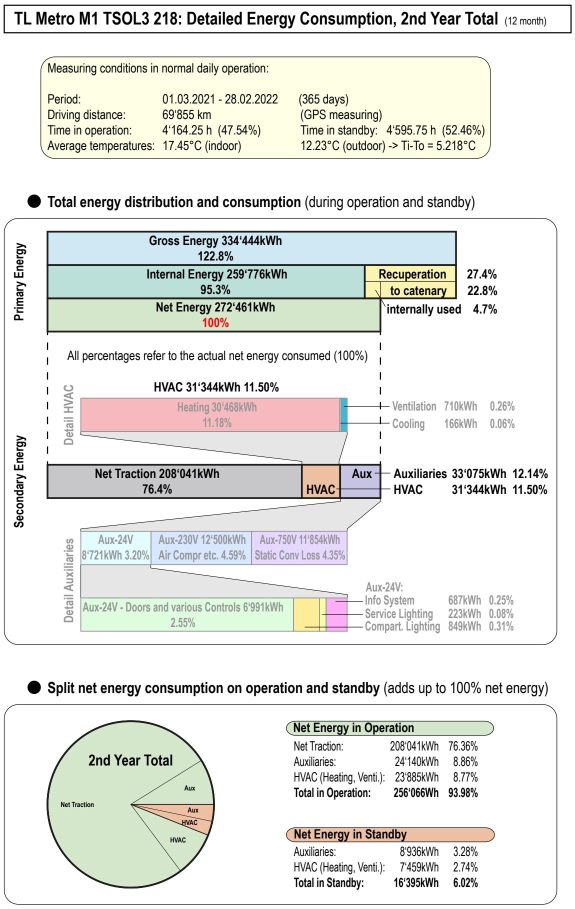


Fig. A12.2: Detailed energy consumption 2nd year (total)

A12.1 Comments on all diagrams for detailed energy consumption

The main benefit of these diagrams is the overview of the major energy consumers over larger periods of time. In order to be able to define energy-saving measures, one must first know which consumers consume how much, when and under which ambient conditions.
It is particularly interesting how much energy is consumed in operation and how much in standby.

When comparing these diagrams, it is important to consider not only the percentages but also the absolute energy values. Although the absolute traction energy decreases somewhat in the second year (due to the shorter driving distance), the percentage of traction energy in the total energy increases. The reason for this is that HVAC energy (mostly heating energy) decreases in the second year of measurement, especially in standby mode.

You can also see how well the recuperation of the drive energy works when braking into the overhead line and for self-consumption. This works more effectively in winter than in summer, as more braking energy can be used directly internally and also externally via the overhead line in other vehicles for heating instead of being senselessly burnt up in the braking resistors.

The exact effectiveness of the energy-saving measures cannot be read from these diagrams. There are too many differences in terms of driving time and idle time, kilometres driven, outside temperature, solar radiation, heating energy from the passengers body heat and the Corona door opening measures introduced in the second year of measurement.
More complex methods and simulations with measurement data are needed to shed more light on this (see A13 - A16).

A13 Comparing the HVAC data of the 2 measurement years

The HVAC energy data of two measurement years cannot be directly compared due to the different climate, solar radiation and duration of use. Unfortunately, the unplanned corona door opening measure was added to the planned heating energy saving measures from April 2020 onwards, which distorted the last month of the first measurement year and cancelled out part of the heating energy saving of the 2nd year.

In the metro there are 2 climate zones (compartments and driver's cabins) and the 2 operating states operation and standby, which must be examined separately. For the initial evaluation of the first year, this was not necessary because the heating in both climate zones was practically the same and constant. Now, however, both years must be treated with equal complexity.

In order to get a useful result, a lot of work is necessary, which is listed below:

- Creation of specific heating power curves including trend lines as a function of the outdoor temperature and the difference of the indoor minus the outdoor temperature for both years, all operating states and all climate zones (+April 2020 separately).
- Removal of the solar influence from all heating power curves by grouping the data into 2 groups with a lot or little sun (details later)
- Calibration of the resulting trend lines (without solar influence) as a function of outdoor temperature via simulation of the respective heating energy only from outdoor temperature (with the trend line of the same year)
- Comparing of the corona effect without heating measures in April 2020 with the rest of the 1st year and vector conversion for the compensation of the corona effect with heating measures for the 2nd measurement year
- Simulation of the heating power and energy with the Corona compensated trend lines of the 2nd year and the outdoor temperatures of the 1st year plus its remaining data left constant.
- Evaluation with back-calculation of the solar influence and comparison of the different simulations.

A13.1 Determining the heating characteristics of the Metro M1

As already mentioned, in order to evaluate the data with all case distinctions, at least 4 specific heating power diagrams must be created for each of the following selected hourly data:

- Year 1 compartments standby
- Year 1 compartments operation + April 2020 separately (beginning of Corona door measures)
- Year 1 cabs standby
- Year 1 cabs operation
- Year 2 compartments standby
- Year 2 compartments operation
- Year 2 cabs standby
- Year 2 cabs operation

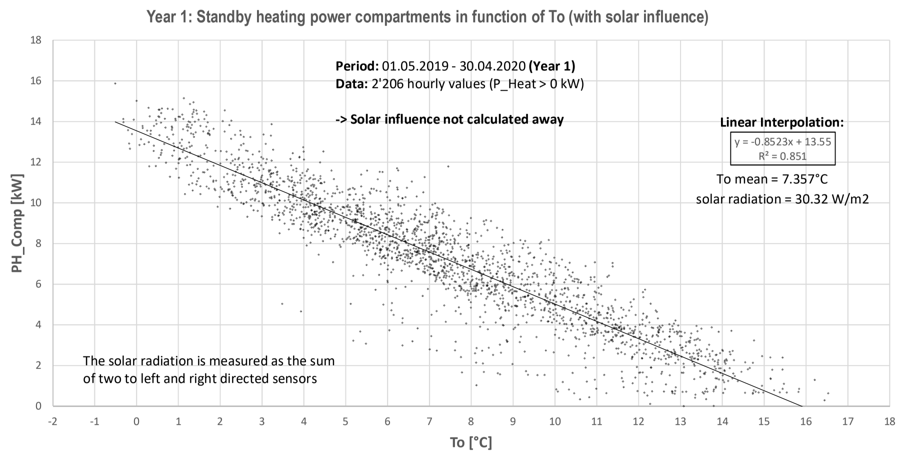
As an example, the 4 specific heating power diagrams of the compartments in standby from the 1st year are shown on the next page.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
7	purged			=0					>0		>0			sort		Zero in SB				A_Solar ->	8.4794643	
8	Date	Op. Bit Oper.=1 (full hour)	Standby Bit Standby=1 (full hour)	No Catenary-Voltage=1	TI_Comp	TI_Cab	TI (indoor Temp)	TO (outdoor Temp)	PH_Comp	PH_Cab	PH (heating)	PC (cooling)	PV (ventil.)	P_Solar L+R	Rel. Door Opening Time	Number of Passengers (statistics)	TI minus TO	TI_Comp minus TO	TI_Cab minus TO	Hour Counter	P_Solar	PH_Comp + P_Solar
9					[°C]	[°C]	[°C]	[°C]	[kW]	[kW]	[kW]	[kW]	[kW]	[W/m2]	[%]		[°C]	[°C]	[°C]		[kW]	[kW]
792	28.03.2020 22:00	0	1	0	17.535	20.900	17.858	11.385	4.715	1.139	5.854	0.000	0.137	0.008	0.000	31.921	6.473	6.150	9.515	783	0.000	4.715
793	07.04.2020 21:00	0	1	0	18.968	23.715	19.424	12.860	0.609	0.000	0.609	0.000	0.018	0.008	0.000	37.501	6.564	6.108	10.855	784	0.000	0.609
794	20.05.2019 03:00	0	1	0	17.407	20.849	17.738	11.654	3.866	0.803	4.669	0.000	0.135	0.008	0.000		6.084	5.753	9.195	785	0.000	3.866
795	20.05.2019 02:00	0	1	0	17.449	20.856	17.776	11.868	3.580	0.790	4.370	0.000	0.127	0.008	0.000		5.908	5.581	8.988	786	0.000	3.580
796	19.04.2020 01:00	0	1	0	18.003	21.475	18.337	12.688	2.750	0.370	3.119	0.000	0.080	0.008	0.000	0.000	5.649	5.315	8.787	787	0.000	2.750
797	28.03.2020 05:00	0	1	0	16.351	20.932	16.791	2.514	10.913	1.951	12.865	0.000	0.319	0.006	0.000	8.143	14.277	13.837	18.418	788	0.000	10.913
798	21.03.2020 19:00	0	1	0	17.800	21.516	18.156	11.020	3.611	0.601	4.211	0.000	0.105	0.004	0.000	51.468	7.136	6.780	10.496	789	0.000	3.611
799	09.02.2020 18:00	0	1	0	17.086	20.873	17.450	10.615	6.074	1.425	7.499	0.000	0.178	0.004	0.000	36.397	6.835	6.471	10.258	790	0.000	6.074
800	28.01.2020 22:00	0	1	0	16.222	20.916	16.673	6.228	11.707	2.221	13.928	0.000	0.325	0.001	0.000	26.613	10.445	9.994	14.688	791	0.000	11.707
801	23.01.2020 04:00	0	1	0	15.855	21.026	16.351	-0.313	13.969	2.533	16.502	0.000	0.404	0.000	0.000		16.664	16.168	21.339	1	0.000	13.969
802	24.03.2020 05:00	0	1	0	15.806	20.893	16.295	-0.317	14.120	2.746	16.866	0.000	0.402	0.000	0.000	8.683	16.612	16.123	21.210	2	0.000	14.120
803	14.01.2020 00:00	0	1	0	15.950	20.926	16.428	-0.157	12.661	2.254	14.916	0.000	0.365	0.000	0.000	11.347	16.585	16.107	21.083	3	0.000	12.661
804	14.01.2020 02:00	0	1	0	15.905	20.943	16.388	-0.176	12.921	2.239	15.160	0.000	0.380	0.000	0.000		16.564	16.081	21.119	4	0.000	12.921
805	14.01.2020 01:00	0	1	0	15.961	20.940	16.439	-0.108	13.385	2.036	15.421	0.000	0.381	0.000	0.000	0.000	16.547	16.069	21.048	5	0.000	13.385
806	07.02.2020 04:00	0	1	0	16.293	21.067	16.751	0.304	11.795	2.055	13.851	0.000	0.341	0.000	0.000		16.447	15.989	20.763	6	0.000	11.795
807	21.01.2020 05:00	0	1	0	15.735	20.949	16.236	-0.202	13.575	2.453	16.027	0.000	0.400	0.000	0.000	9.279	16.438	15.937	21.151	7	0.000	13.575
808	13.01.2020 23:00	0	1	0	15.977	20.888	16.448	0.071	12.848	1.981	14.829	0.000	0.368	0.000	0.000	21.127	16.377	15.906	20.817	8	0.000	12.848
809	21.01.2020 04:00	0	1	0	15.748	20.975	16.250	-0.065	14.092	2.489	16.580	0.000	0.404	0.000	0.000		16.315	15.813	21.040	9	0.000	14.092
810	24.03.2020 04:00	0	1	0	15.808	20.888	16.295	0.002	15.016	2.641	17.657	0.000	0.418	0.000	0.000		16.293	15.806	20.886	10	0.000	15.016
811	14.01.2020 03:00	0	1	0	15.906	20.943	16.390	0.109	13.125	2.088	15.213	0.000	0.379	0.000	0.000		16.281	15.797	20.834	11	0.000	13.125
812	23.01.2020 03:00	0	1	0	15.923	20.986	16.409	0.147	13.782	2.480	16.262	0.000	0.391	0.000	0.000		16.262	15.776	20.839	12	0.000	13.782

... Y1 Comp Standby Sun | Y1 Comp Operation Sun | Y1 Cab Standby Sun | Y1 Cab Operation Sun | Y2 Basic Data | Y2 Basic Data marked | Y2 Comp ...

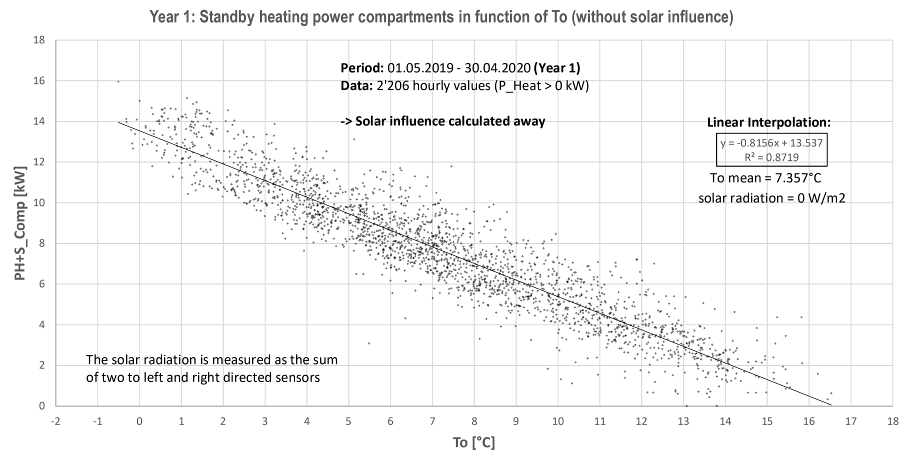
Fig. A13.1: Small excerpt from an excel table with data for a case distiction (background: orange = more sun / light blue = no sun

A14 Example for 4 heating power diagrams of the compartments in standby in the 1st year (the other 8 similar pages are not displayed)



The curve shows the required heating power for the compartments as a function of the outside temperature (To) in standby. Whenever the sun warms up the vehicle, the heating needs to be reduced. Therefore, there is a cloud of measuring points with reduced heating power under the curve.

Fig. A14.1: 1st diagram with raw data in function of To - Checking the distribution of points

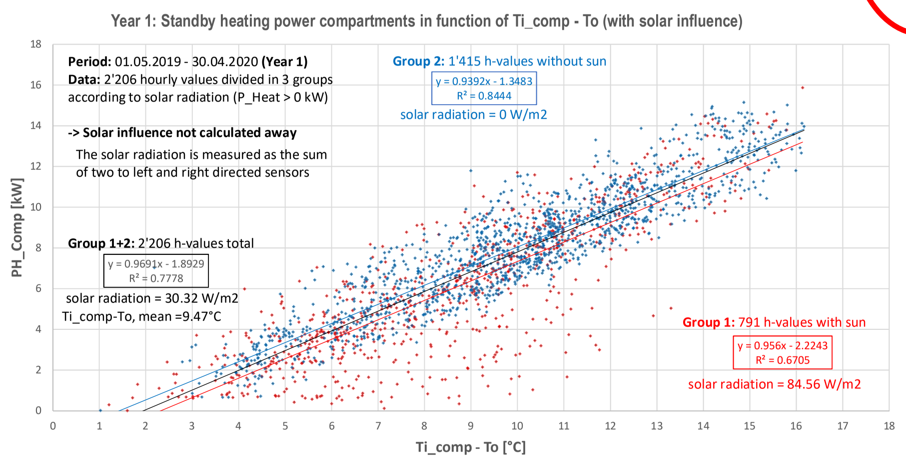


This curve also shows the required heating power for the compartments as a function of the outside temperature (To) in standby. This time, however, the measured solar power was added to determine the effective heating requirement without solar radiation. Thus, the curve rises slightly at warmer outside temperatures and the measuring points are now closer to the interpolation line. This interpolation is suitable for simulations.

start

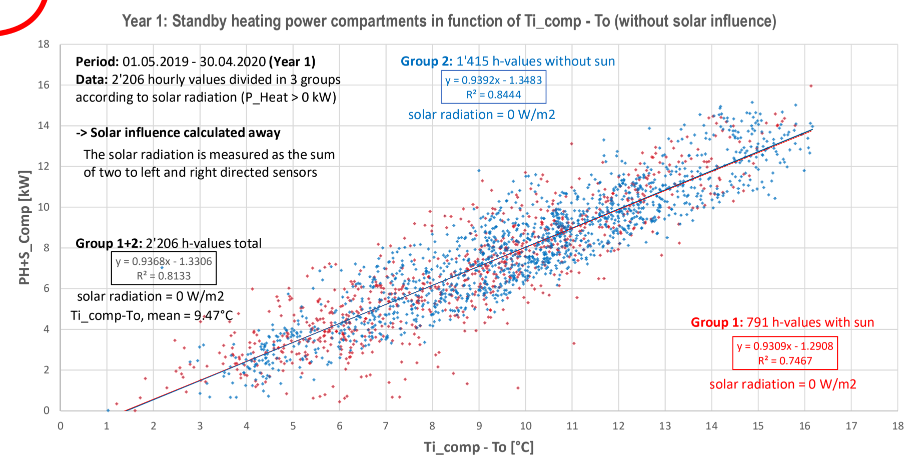
stop

Fig. A14.4: 4th diagram with modified data in function of To - Determine the solar corrected trend line



At the mean temperature value (Ti_comp-To = 9.47°C) of all hourly values, the red curve with sun is 0.717 kW lower than the blue curve without sun. So the solar radiation at the red curve of 84.56 W/m2 (sum of left + right sensor) saves 0.717 kW of heating power on average of the measured heating hours. Dividing this heating power saving by this solar radiation, one obtains the average **solar effective area of 8.479 m2** for the sum of both sensors **in standby**.

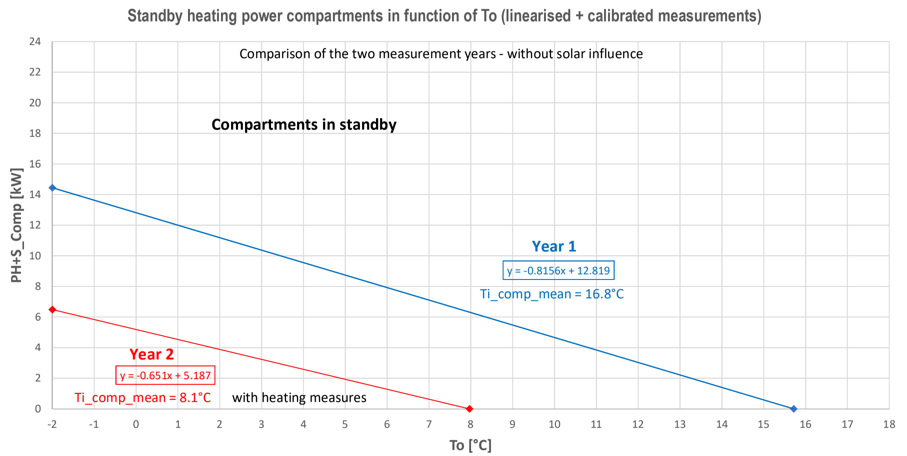
Fig. A14.2: 2nd diagram with raw data in function of Ti-To - Evaluation of the effective solar surface



If the power due to solar radiation is added to each measuring point, the red and black curves practically shift to the blue curve without solar radiation. This serves to check whether the solar influence was added correctly and shows the total heating power required. In a simulation at another time, the solar power prevailing there can then be subtracted again to obtain the correct electrical heating power.

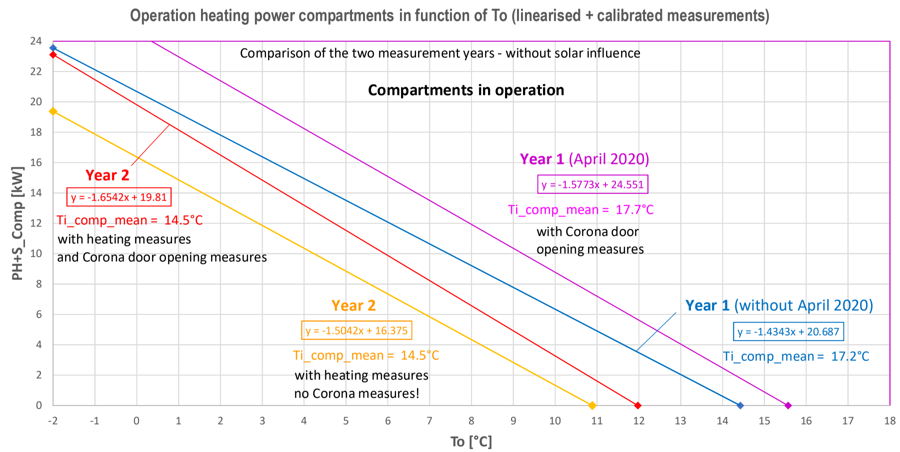
Fig. A14.3: 3rd diagram with modified data in function of Ti-To - Checking of the solar correction

A15 Trend lines of the heating characteristics of Metro M1 without solar radiation (already calibrated by the simulation as mentioned in A13)



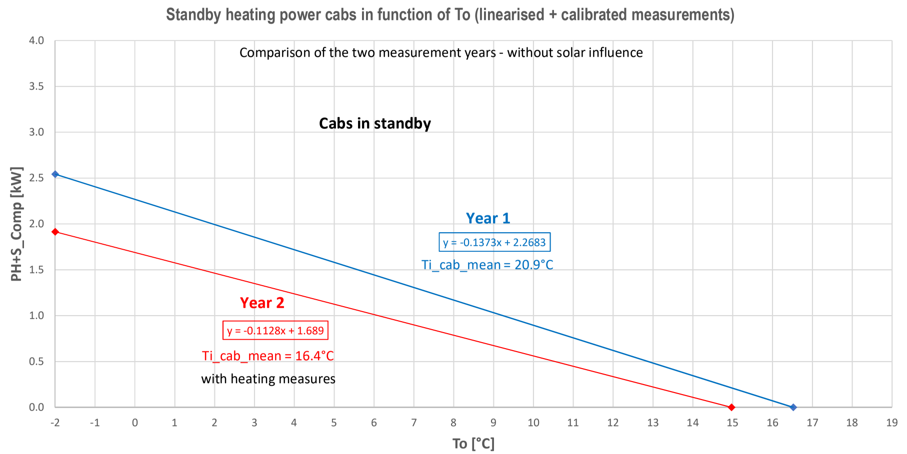
These curves show the required heating power without the help of the sun for the compartments depending on the outdoor temperature (To) in standby mode. By lowering the setpoint temperature to 8°C during standby, much less heating is required in the 2nd year.

Fig. A15.1: Standby heating-power compartments - the big temperature reduction saves enormously



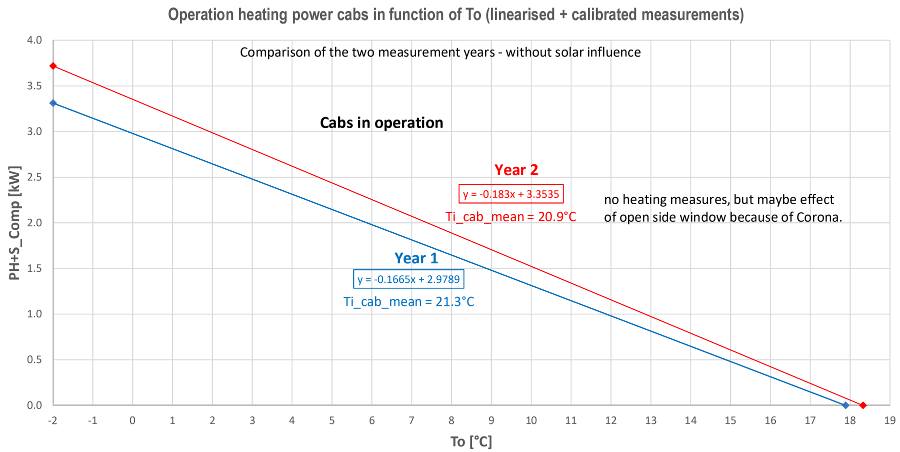
By lowering the setpoint temperature by 3°C during operation less heating is required in the 2nd year. Unfortunately, the Corona door opening measures reduced the savings effect. This can be seen nicely in April 2020 (last month of measurement year 1) when the Corona measures started without the temperature reduction. Based on the two curves of the first year and red curve with corona measures, an orange corona-free curve was calculated for the simulation.

Fig. A15.4: Operation heating-power compartments - the temperature reduction saves energy



These curves show the required heating power without the help of the sun for the cabs depending on the outdoor temperature (To) in standby mode. By lowering the setpoint temperature to 17°C during standby, less heating is required in the 2nd year. Due to the colder compartment temperature in the 2nd year, the driver's cabs have to heat up a little more, which increases the offset of the red curve slightly.

Fig. A15.2: Standby heating-power cabs - the small temperature reduction saves a little bit



These curves show the required heating power without the help of the sun for the cabs depending on the outdoor temperature (To) in operation mode. Although the setpoint temperature remains unchanged during operation, the heating is slightly higher in the second year. The driver's cabs were probably ventilated more (possibly a slightly open side window).

Fig. A15.3: Operation heating-power cabs - more heating needed in the 2nd year (open side window)

On the last page all trend lines for the different heating zones, the operating modes and time periods are shown (without solar radiation). These calibrated trend lines are used for simulation in the last step (A15).

The Corona door opening measures mainly affect the heating power of the compartments in operation. Figure A15.4 shows the influence of the Corona door opening measures in April 2020 (first year of measurement) on the violet curve compared to the blue curve without the Corona measures. The virtual orange trend line was laid out by vector calculation in such a way that the difference in power between the violet and blue trend lines corresponds to the difference in power between the red and orange trend lines for any fixed heating power.

For the cabs in operation (Fig. A15.3), the red heating power curve of the second year is clearly higher than the blue one of the first year. Since nothing is likely to have changed in the cabs, it could be that the cabs were more ventilated during the Corona measures. For the simulation of the virtual second year without Corona measures, the blue curve is therefore used.

A16 Simulation of annual energy

The trend lines obtained with the heating power curves without solar influence are now used in the annual simulations. First, these trend lines are checked in the simulation and the offset is slightly calibrated so that the simulation with the same year provides the same heating values as the measurement. In the annual simulation, 15 minute values of different heating powers are used and summed up to the energy to increase the accuracy. At the same time, the solar power matching the simulation is again subtracted from the heating power.

The formulas of the trend lines can be used to calculate the respective heating power (y, [kW]) at any outdoor temperature (x, [°C]). Above the intersection of each of these trend lines with the x-axis, the power is zero watts. The maximum heat output is 5 kW for both cabins and 25 kW for both compartments.

A formula from measurements was generated for the ventilation power of the fan heaters, which calculates the result from the heating power of the fans:

$$PV\_Comp = -0.00023x^2 + 0.0273147x \quad [kW] \qquad x = PH\_Comp\ [kW]$$
$$PV\_Cab = -0.000046x^2 + 0.00546294x \quad [kW] \qquad x = PH\_Cab\ [kW]$$

The main advantage is that the trend line formulas for the heating powers of the 2nd year can be calculated with the outdoor temperatures of the 1st year and most of the other data can be taken over from the 1st year. This makes a perfect comparison of the HVAC data of both years possible, also in relation to the total net power. Virtually all disturbing influences are eliminated. Normally, passenger heating power can be considered constant when comparing two yearly averages. Fewer passengers during the Corona measures at colder times would increase the heating power required - so our heating savings results are on the safe side.

L35131 =WENN((WENN(B35131=1;WENN(E35131<$L$9;$L$7*E35131+$L$8;0);0)-M35131)>0;(WENN(B35131=1;WENN(E35131<$L$9;$L$7*E35131+$L$8;0);0)-M35131); 0)

	A	B	C	D	E	F	G	H	I
1	Diagram: M1_PH_PL_Einsatz_Stillstand 15Min				Year 1: 01.05.2019 - 30.04.2020				
2	Simulation:	Year 2 (no Corona) with year 1 as reference (no Corona)							
3									
4									
5									
6									
7									
8								nur Offset anpassen:	
9									
10		Fahrzeug im Einsatz =1 wenn v > 2km/h, P_MotA > 0.2kW (15 Min Wert)	Temperatur Abteile innen (15Min Mittelwert)	Temperatur Führerstände innen (15Min Mittelwert)	Temperatur aussen, minimal (15Min Mittelwert)	Heizleistung beider Abteile aus Energiedifferenz (15Min-Wert)	Leistung Lüftung Abteil aus Energiedifferenz (15Min-Wert)	Heizleistung beider Führerstände aus Energiedifferenz (15Min-Wert)	Solarstrahlung summiert links+rechts 15Min Wert (wirkt auf halbe Fensterfläche)
11									
12	Date	Operation/ Standby	TI_Comp	TI_Cab	TO	PH_Comp	PV_Comp	PH_Cab	P_Solar
13		1=OP/0=SB	[°C]	[°C]	[°C]	[kW]	[kW]	[kW]	[W/m2]
35143	30.04.2020 22:15	1	17.243	21.298	9.348	14.154	0.307	0.654	0.000
35144	30.04.2020 22:30	1	17.536	20.934	9.497	5.303	0.146	0.492	0.122
35145	30.04.2020 22:45	1	17.429	21.085	10.489	8.416	0.203	0.995	0.277
35146	30.04.2020 23:00	1	17.352	20.773	9.975	12.678	0.284	0.275	0.000
35147	30.04.2020 23:15	1	17.497	20.450	10.195	6.231	0.157	0.000	0.000
35148	30.04.2020 23:30	1	17.425	20.255	10.826	5.768	0.140	0.448	0.399
35149	30.04.2020 23:45	1	17.522	20.515	10.182	7.546	0.168	2.860	0.000
35150	Summe					140'534.659	3'484.201	26'129.205	
35151	Summe/4=[kWh]	Accumulated energie 1st year total:				35'133.66	871.05	6'532.30	
35152									
35153									
35154									
35155									

	J	K	L	M	N	O	P	Q
5		ok	ok			ok	ok	
6	Equation	+ sun influ.	- sun influ.		Equation	+ sun influ.	- sun influ.	
7	Slope:	-1.6798	-1.50422815		Slope:	-0.6578	-0.651	
8	Offset:	19.8178183	16.3751279		Offset:	5.1681063	5.1869834	
9	Intersection:	11.798	10.886		Intersection:	7.857	7.968	
10	Original Offset:	19.522	19.543	A_Solar Comp OP [m2]	Original Offset:	5.0432	5.0465	A_Solar Comp SB [m2]
11				8.4794643				8.4794643
12	PH_Comp OP	PH_Comp OP SIM	PH+S_Comp minus PH_Comp_Solar OP SIM	PH_Comp _Solar OP SIM	PH_Comp SB	PH_Comp SB SIM	PH+S_Comp minus PH_Comp_Solar SB SIM	PH_Comp _Solar SB SIM
13	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]
35143	14.154	4.115	2.314	0.000	0.000	0.000	0.000	0.000
35144	5.303	3.865	2.088	0.001	0.000	0.000	0.000	0.000
35145	8.416	2.198	0.595	0.002	0.000	0.000	0.000	0.000
35146	12.678	3.062	1.370	0.000	0.000	0.000	0.000	0.000
35147	6.231	2.692	1.040	0.000	0.000	0.000	0.000	0.000
35148	5.768	1.632	0.087	0.003	0.000	0.000	0.000	0.000
35149	7.546	2.714	1.059	0.000	0.000	0.000	0.000	0.000
35150	71'281.207	53'289.976	36'230.796	16'662.929	69'253.452	11'253.815	11'070.018	12'482.644
35151	17'820.30	13'322.49	9'057.70	4'165.73	17'313.36	2'813.45	2'767.50	3'120.66
35153			50.83%				15.98%	
35154			49.17%	saving on Y1			84.02%	saving on Y1

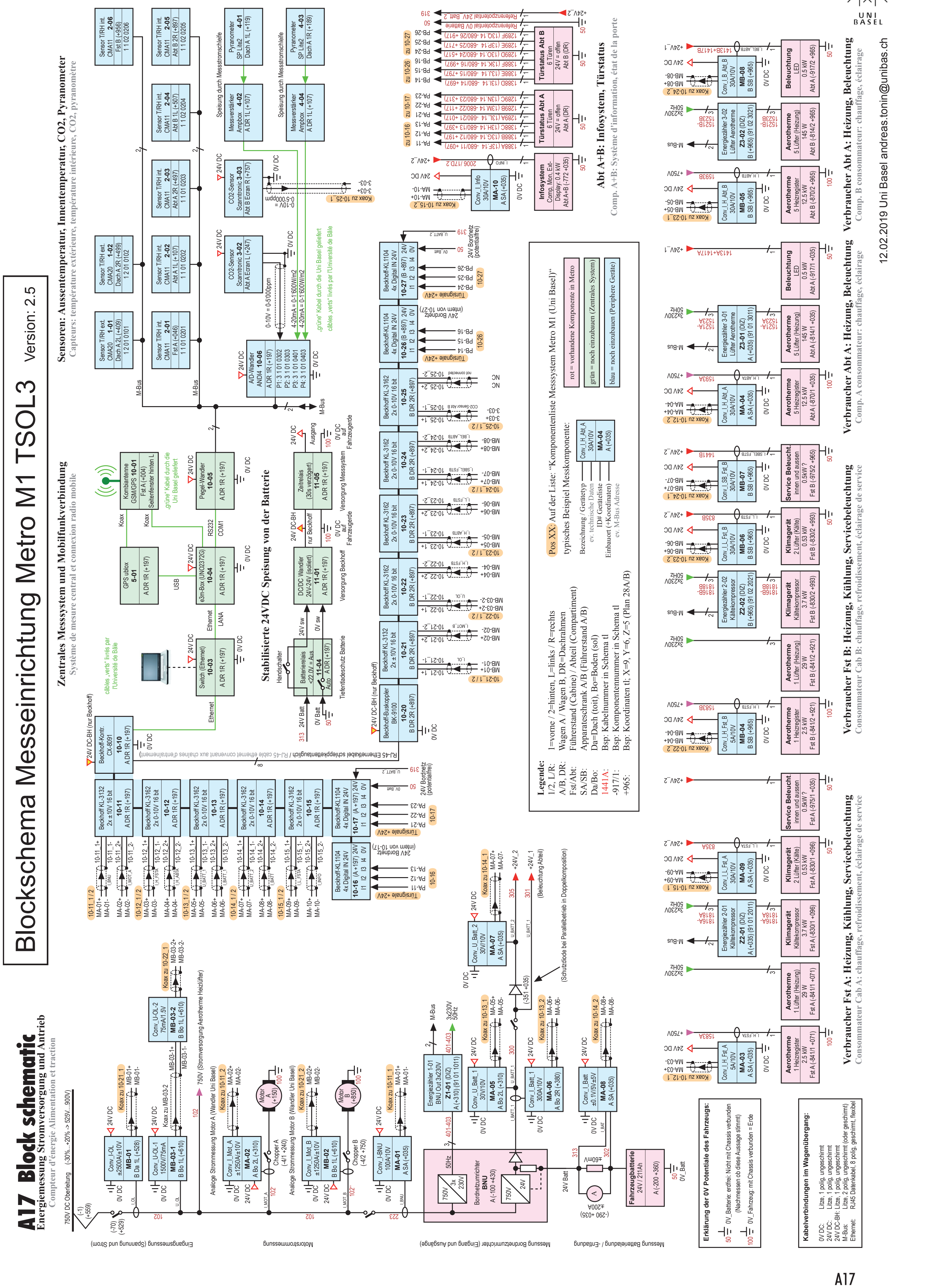
	R	S	T	U	V	W	X	Y	Z	AA	AB	AC
2	Polynom	Vent. Comp										
3	PV_Comp X^2:	-0.00023										
4	PV_Comp X:	0.0273147										
5						ok	ok			ok	ok	
6					Equation	+ sun influ.	- sun influ.		Equation	+ sun influ.	- sun influ.	
7					Slope:	-0.1768	-0.1665		Slope:	-0.1181	-0.1128	
8					Offset:	2.9613735	2.9788898		Offset:	1.69624057	1.6889983	
9					Intersection:	16.750	17.891		Intersection:	14.363	14.973	
10					Original Offset:	3.0054	3.0343	A_Solar Cab OP [m2]	Original Offset:	2.0621	2.06	A_Solar Cab SB [m2]
11								1.843594884				1.31564509
12	PV_Comp OP	PV_Comp OP SIM	PV_Comp SB	PV_Comp SB SIM	PH_Cab OP	PH_Cab OP SIM	PH+S_Cab minus PH_Cab_Solar OP SIM	PH_Cab _Solar OP SIM	PH_Cab SB	PH_Cab SB SIM	PH+S_Cab minus PH_Cab_Solar SB SIM	PH_Cab _Solar SB SIM
13	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]
35143	0.307	0.341	0.000	0.000	0.654	1.309	1.422	0.000	0.000	0.000	0.000	0.00
35144	0.146	0.138	0.000	0.000	0.492	1.282	1.397	0.000	0.000	0.000	0.000	0.00
35145	0.203	0.214	0.000	0.000	0.995	1.107	1.232	0.001	0.000	0.000	0.000	0.00
35146	0.284	0.309	0.000	0.000	0.275	1.198	1.318	0.000	0.000	0.000	0.000	0.00
35147	0.157	0.161	0.000	0.000	0.000	1.159	1.281	0.000	0.000	0.000	0.000	0.00
35148	0.140	0.150	0.000	0.000	0.448	1.047	1.176	0.001	0.000	0.000	0.000	0.00
35149	0.168	0.193	0.000	0.000	2.860	1.161	1.284	0.000	0.000	0.000	0.000	0.00
35150	1'728.752	1'737.716	1'755.449	1'746.487	13'073.865	13'073.865	13'073.865	3'622.834	13'055.340	8'581.097	8'562.743	1'936.76
35151	432.19	434.43	438.86	436.62	3'268.47	3'268.47	3'268.47	905.71	3'263.84	2'145.27	2'140.69	484.1
35153							100.00%				65.59%	
35154							0.00%	saving on Y1			34.41%	saving on Y1

... | Y1 TO with Y1 SIM (Apr no Cor) | Y2 TO with Y2 SIM | Y1 TO with Y2 SIM (Cor) | Y1 TO with Y2 SIM (no Cor) | Y2 TO with Y1 SIM +Y1 (no Cor) | Summary

Fig. A16: Small excerpt from the Excel table with an example of an annual simulation (the line numbers goes over 35'000)

The results of these simulations can be found in the final report in chapters 7.1 to 7.3 (pages 12 to 13).

The plans on the next pages show the complexity of the metro and the measurement system (mostly only in German).



A17 Block schematic
Energiemessung Stromversorgung und Antrieb
Compteur d'énergie Alimentation et traction
Blockschema Messeinrichtung Metro M1 TSOL3
Version: 2.5
Sensoren: Aussentemperatur, Innentemperatur, CO2, Pyranometer
Capteurs: température extérieure, température intérieure, CO2, pyranometre
Zentrales Messsystem und Mobilfunkverbindung
Système de mesure central et connexion radio mobile
Stabilisierte 24VDC Speisung von der Batterie
Abt A+B: Infosystem, Türstatus
Comp. A+B: Système d'information, état de la porte
Fahrzeugbatterie
Verbraucher Fst A: Heizung, Kühlung, Servicebeleuchtung
Consommateur Cab A: chauffage, refroidissement, éclairage de service
Verbraucher Fst B: Heizung, Kühlung, Servicebeleuchtung
Consommateur Cab B: chauffage, refroidissement, éclairage de service
Verbraucher Abt A: Heizung, Beleuchtung
Comp. A consommateur: chauffage, éclairage
Verbraucher Abt B: Heizung, Beleuchtung
Comp. B consommateur: chauffage, éclairage
Legende:
Erklärung der 0V Potentiale des Fahrzeugs:
Kabelverbindungen im Wagenübergang:
12.02.2019 Uni Basel andreas.tonin@unibas.ch

A18 Installation plan

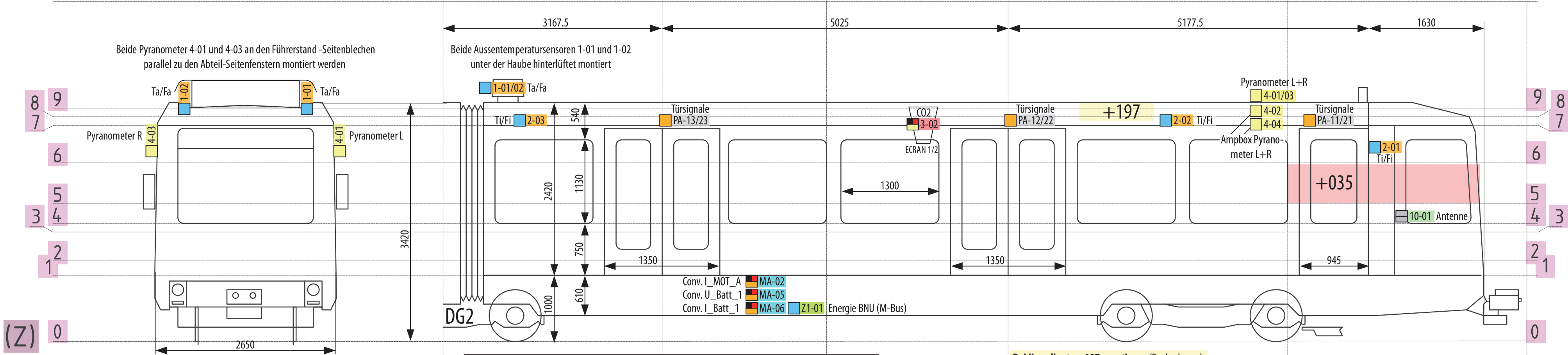
Wagon A

Koordinaten: + X Y Z

Einbauplan Messeinrichtung Metro M1 TSOL3 Wagen A

Version: 2.5

(DIR. RENENS)



Liste aller Komponenten im Wagen A		Ort: (+xyz)
1-01	Aussentemperatursensor links (Ta/Fa)	(+409)
1-02	Aussentemperatursensor rechts (Ta/Fa)	(+499)
2-01	Innentemperatursensor Führerstand (Ti/Fi)	(+046)
2-02	Innentemperatursensor Abteil vorne links (Ti/Fi)	(+107)
2-03	Innentemperatursensor Abteil hinten rechts (Ti/Fi)	(+497)
3-02	CO2-Sensor Abteil mitte links am Infomonitor	(+247)
4-01	Pyranometer links (seitliche Sonneneinstrahlung)	(+119 oder +006)
4-02	Messverstärker zu Pyranometer links (Ampbox)	(+107)
4-03	Pyranometer rechts (seitliche Sonneneinstrahlung)	(+189 oder +096)
4-04	Messverstärker zu Pyranometer rechts (Ampbox)	(+107)
5-01	GPS-Empfänger	(+197)
10-01	Kombi Fensterklebantenne (Mobilfunk und GPS)	(+004)
10-03	Switch (Ethernet)	(+197)
10-04	Messcomputer e3m-Box, inkl. Mobilfunk-Modem	(+197)
10-05	PW60 (M-Bus Schnittstelle)	(+197)
10-06	ANDI4 (4 M-Bus ADC's)	(+197)
10-10 - 10-17	Beckhoff-System, Gerät A	(+197)
11-01	DC/DC-Wandler 24V/24V (Speisung Messsystem, 150W)	(+197)
11-04	Batterie Relais (Speisungsabschaltung unter 22V)	(+197)
11-05	Zeitrelais (Speisungseinschaltverzögerung)	(+197)
MA-01	Conv. I_BNU 100A/10V	(+035)
MA-02	Conv. I_MOT_A ±1250A/±10V	(+310)
MA-03	Conv. I_H_Fst_A 5A/10V	(+035)
MA-04	Conv. I_H_Abt_A 30A/10V	(+035)
MA-05	Conv. U_Batt_1 30V/10V	(+310)
MA-06	Conv. I_Batt_1 300A/10V	(+380)
MA-07	Conv. U_Batt_2 30V/10V	(+035)
MA-08	Conv. I_Batt (über Shunt) ±333.3A/5V±5V	(+035)
MA-09	Conv. I_L_Fst_A 30A/10V	(+035)
MA-10	Conv. I_Info 30A/10V	(+035)
Z1-01	Energiezähler BNU OUT (3x230V, 50Hz, M-Bus)	(+310)
Z2-01	Energiezähler Kühlung Fst A (3x230V, 50Hz, M-Bus)	(+035)
Z3-01	Energiezähler Lüfter AT Abt A (3x230V, 50Hz, M-Bus)	(+035)

PA-11 (+097), PA-12 (+197), PA-13 (+397), PA-21 (+017), PA-22 (+117), PA-23 (+317) Türsignale (24V = offen, 0V=zu, Ort jeweils über den Türen)

DG2

Farbcode Speisung (Kabel Nummer):

- 0V DC (Speisung: 0V Messsystem geerdet)
- 24V DC (Speisung: 24V Messsystem allgemein)
- 24V DC-BH (Speisung: 24V Beckhoff, 30s früher)
- 24V Batt (Speisung: 24V von Fahrzeugbatterie, 313)
- 24V Batt_2 (Ref. Türmessung: Fahrzeugbatterie, 319)
- 0V Batt (Speisung: 0V von Fahrzeugbatterie, 50)
- 0V sw (Speisung: 0V geschaltet von Batterierelais)
- 24 sw (Speisung: 24V geschaltet von Batterierelais)

Farbcode Signale:

- M-Bus (2 Draht-Datenleitung)
- Beckhoff analog (Koaxkabel dünn, RG174)
- Ethernet (RJ45 Datenkabel)
- Antenne (2 Koaxkabel dick, GPS+3G)
- sonstige Signale und interne Verkabelung

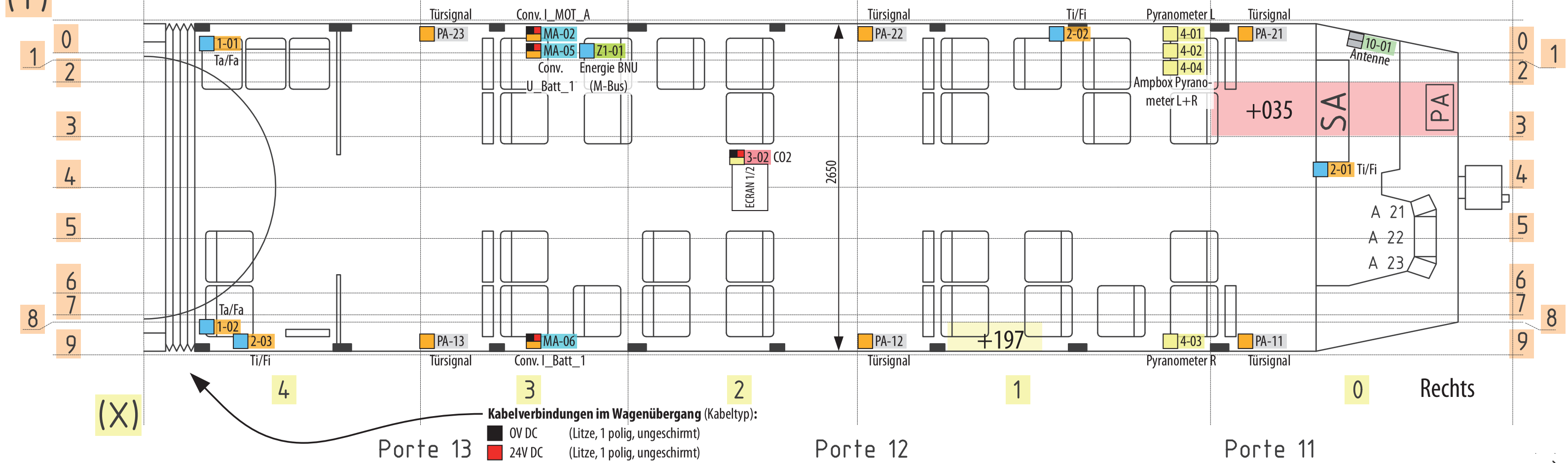
Beispiel Speisung und Ausgang eines Wandlers: 0V DC, 24VDC, Koaxabel zu Beckhoff

Bei Koordinate +197 montieren (Dachrahmen): DG1

- 5-01 GPS-Empfänger
- 10-03 Switch (Ethernet)
- 10-04 e3m-Box (Messcomputer und Modem)
- 10-05 PW60 (M-Bus Schnittstelle)
- 11-01 24V/24V (Speisung Messsystem)
- 11-04 Batt. Relais (Speisung)
- 11-05 Zeitrelais (Speisung)
- 10-10 - 10-17 Beckhoff-System (Teil A)
- 10-06 ANDI 4, ADC (M-Bus)

Bei Koordinate +035 montieren (SA Rückseite):

- MA-01 Conv. I_BNU
- MA-03 Conv. I_H_Fst_A
- MA-04 Conv. I_H_Abt_A
- MA-07 Conv. U_Batt_2
- MA-08 Conv. I_Batt
- MA-09 Conv. I_L_Fst_A
- MA-10 Conv. I_Info
- Z2-01 Energiezähler Kühlung Fst A (M-Bus)
- Z3-01 Energiezähler Lüfter AT Abt A (M-Bus)



Kabelverbindungen im Wagenübergang (Kabeltyp):

0V DC	(Litze, 1 polig, ungeschirmt)
24V DC	(Litze, 1 polig, ungeschirmt)
24V DC-BH	(Litze, 1 polig, ungeschirmt)
M-Bus	(Litze, 2 polig, ungeschirmt, oder Kabel 2 polig geschirmt)
Ethernet	(RJ45 Datenkabel, 8 polig geschirmt, flexibel)

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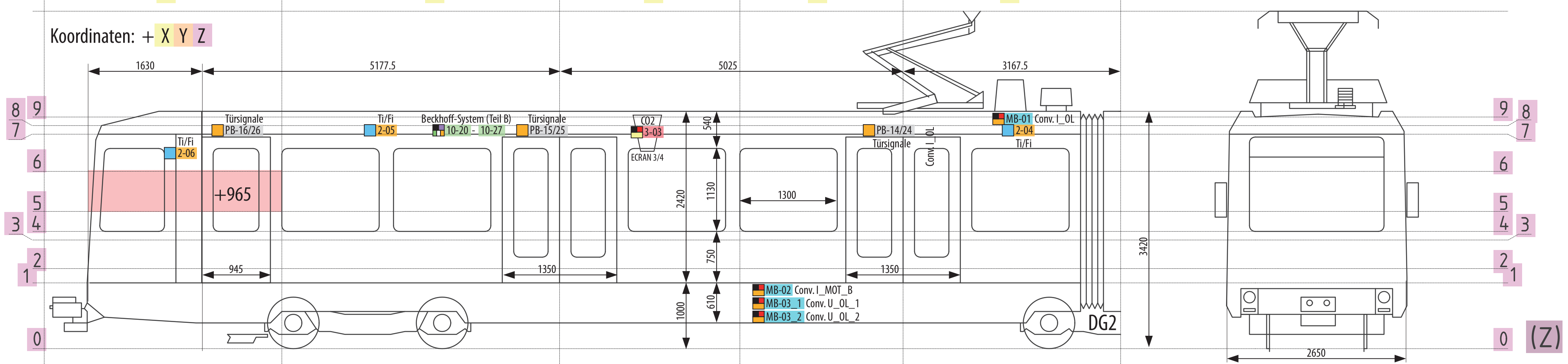
A19 Installation plan

Wagon B (DIR. FLON)

Einbauplan Messeinrichtung Metro M1 TSOL3 Wagen B Version: 2.5

Koordinaten: + X Y Z



Bei Koordinate +965 montieren (SB Rückseite):

- MB-04 Conv. I_H_Fst_B
- MB-05 Conv. I_H_Abt_B
- MB-06 Conv. I_L_Fst_B
- MB-07 Conv. I_SB_Fst_B
- MB-08 Conv. I_B_Abt_B
- Z2-02 Energiezähler Kühlung Fst B (M-Bus)
- Z3-02 Energiezähler Lüfter AT Abt B (M-Bus)

DG3

Farbcode Speisung (Kabel Nummer):

- 0V DC (Speisung: 0V Messsystem geerdet)
- 24V DC (Speisung: 24V Messsystem allgemein)
- 24V DC-BH (Speisung: 24V Beckhoff, 30s früher)
- 24V Batt_2 (Ref. Türmessung: Fahrzeugbatterie, 319)
- 0V Batt (Speisung: 0V von Fahrzeugbatterie, 50)

Farbcode Signale:

- M-Bus (2 Draht-Datenleitung)
- Beckhoff analog (Koaxkabel dünn, RG174)
- Ethernet (RJ45 Datenkabel)
- Antenne (2 Koaxkabel dick, GPS+3G)
- sonstige Signale und interne Verkabelung

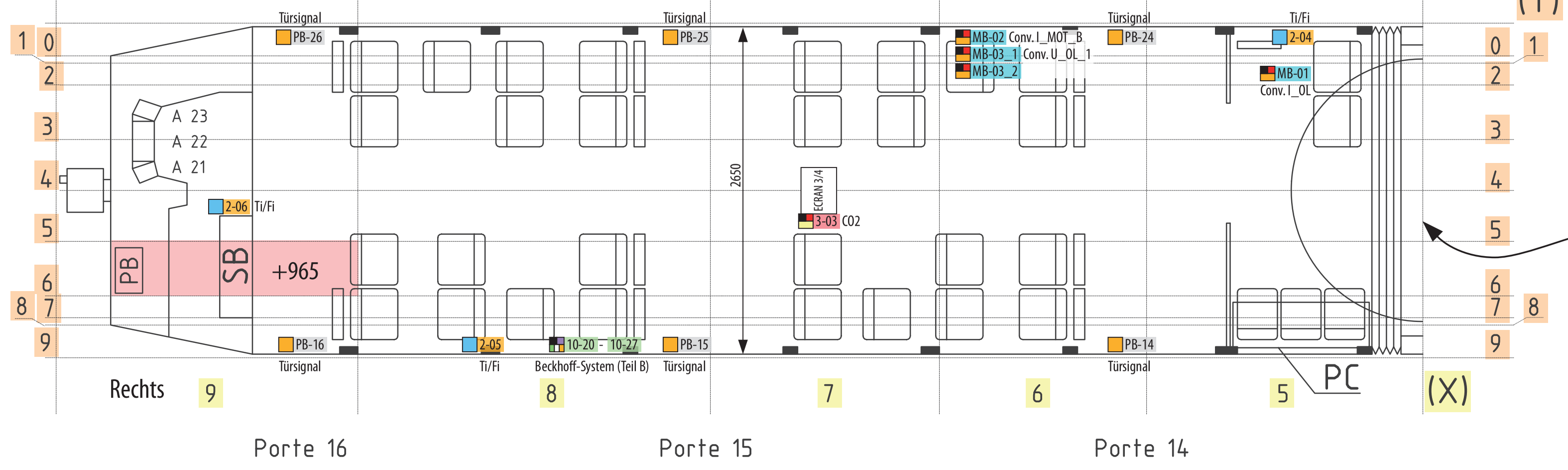
Beispiel Speisung und Ausgang eines Wandlers:
0V DC, 24VDC, Koaxkabel zu Beckhoff

Liste aller Komponenten im Wagen B			Ort: (+xyz)
2-04	Innentemperatursensor Abteil vorne links (Ti/Fi)		(+507)
2-05	Innentemperatursensor Abteil hinten rechts (Ti/Fi)		(+897)
2-06	Innentemperatursensor Führerstand (Ti/Fi)		(+956)
3-03	CO2-Sensor Abteil mitte rechts an Infomonitor		(+757)
10-20 - 10-27	Beckhoff-System, Gerät B, im Dachrahmen		(+897)
MB-01	Conv. I_OL	±2500A/±10V	(+528)
MB-02	Conv. I_MOT_B	±1250A/±10V	(+610)
MB-03_1	Conv. U_OL_1	1500V/75mA	(+610)
MB-03_2	Conv. U_OL_2	75mA/1.5V	(+610)
MB-04	Conv. I_H_Fst_B	5A/10V	(+965)
MB-05	Conv. I_H_Abt_B	30A/10V	(+965)
MB-06	Conv. I_L_Fst_B	30A/10V	(+965)
MB-07	Conv. I_SB_Fst_B	30A/10V	(+965)
MB-08	Conv. I_B_Abt_B	30A/10V	(+965)
Z2-02	Energiezähler Kühlung Fst B (3x230V, 50Hz, M-Bus)		(+965)
Z3-02	Energiezähler Lüfter AT Abt B (3x230V, 50Hz, M-Bus)		(+965)

PB-14	PB-15	PB-16	PB-24	PB-25	PB-26
(+697)	(+797)	(+997)	(+517)	(+717)	(+917)

Türsignale (24V = offen, 0V=zu, Ort jeweils über den Türen)

Links Porte 26 Porte 25 Porte 24



Rechts Porte 16 Porte 15 Porte 14

Kabelverbindungen im Wagenübergang (Kabeltyp):

0V DC	(Litze, 1 polig, ungeschirmt)
24V DC	(Litze, 1 polig, ungeschirmt)
24V DC-BH	(Litze, 1 polig, ungeschirmt)
M-Bus	(Litze, 2 polig, ungeschirmt, oder Kabel 2 polig geschirmt)
Ethernet	(RJ45 Datenkabel, 8 polig geschirmt, flexibel)

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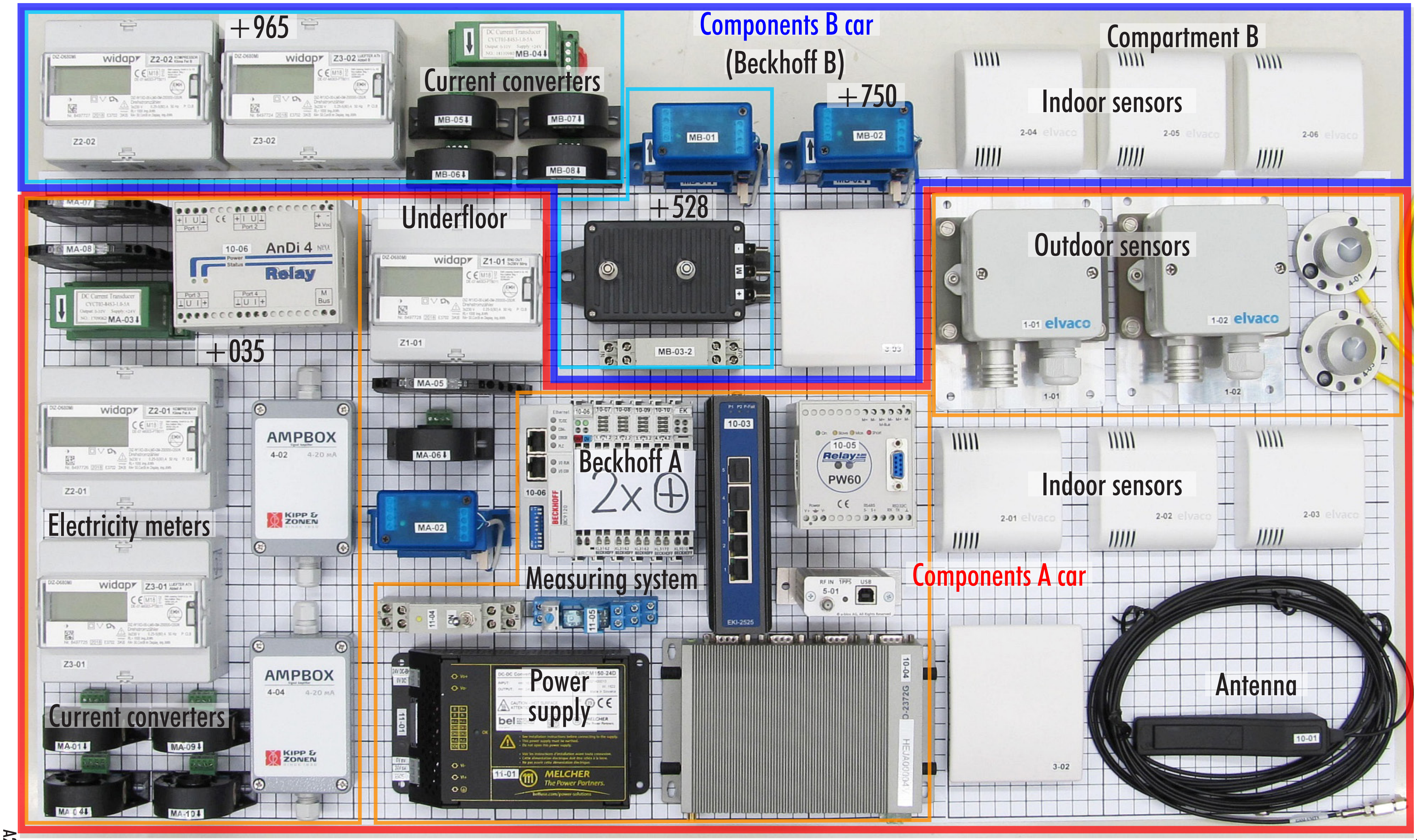
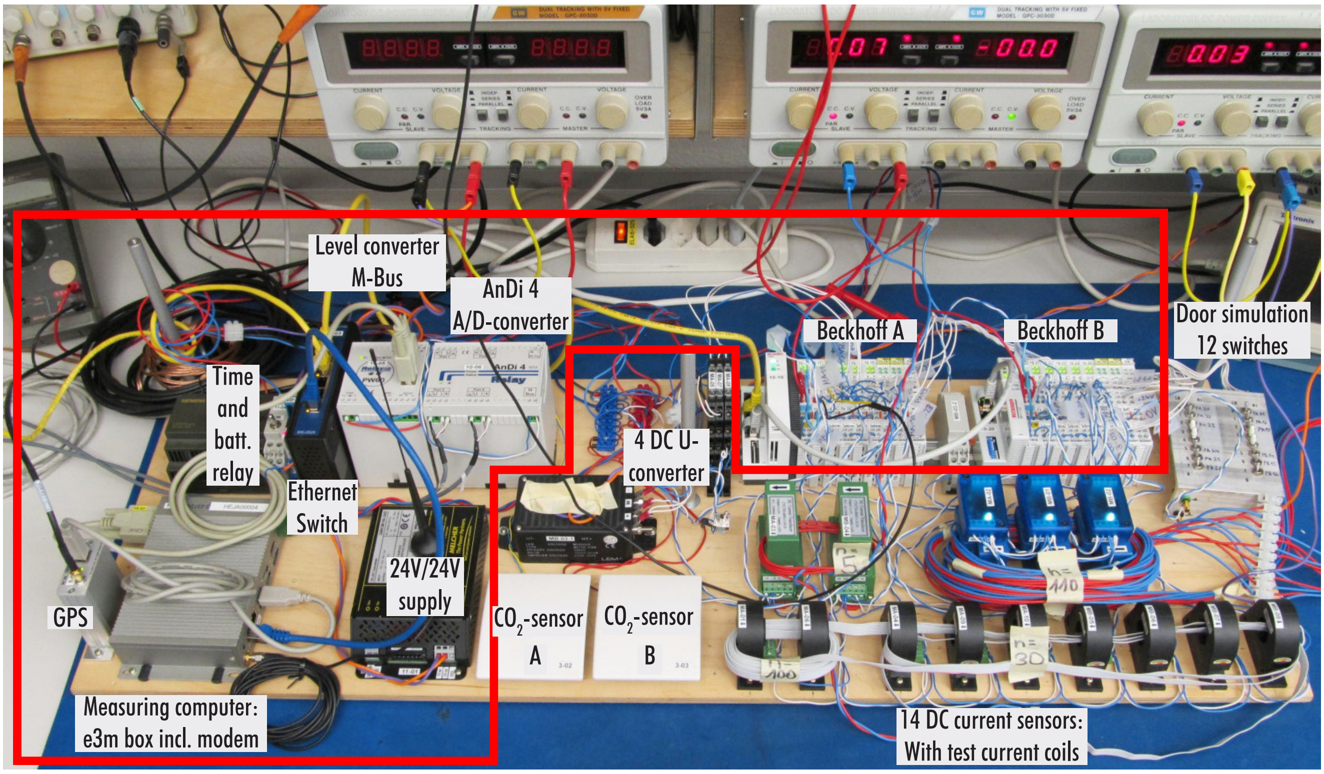
A20 Photo overview of all components of the University of Basel (Beckhoff is wider than shown - there is a 2nd one in the B-car)

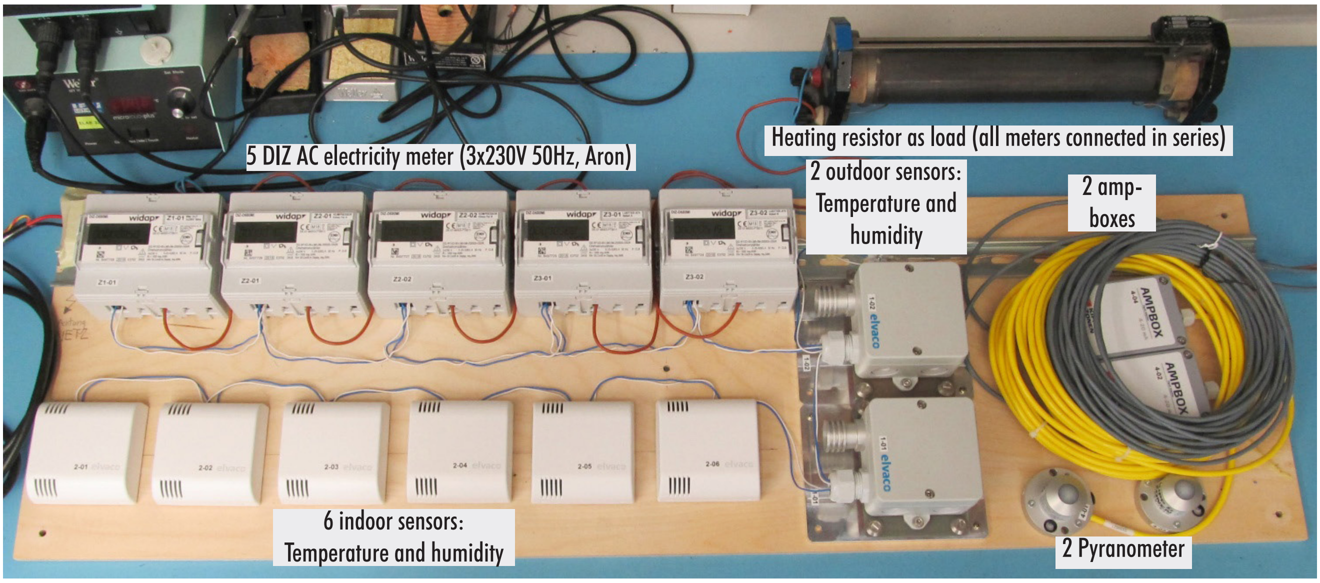


A21 Laboratory Measurement Setup (with all components except for the adhesive windows antenna)

The photos show the components in use on 2 laboratory test desks in direct size comparison.
Here the components are extensively tested in interaction with the software (external data server), experience is gathered and long-term measurements are carried out.
On the upper plate you can see many sensors, converters and the two Beckhoff parts as well as the basic measuring system which is to be placed in the roof frame on the front right in carriage A (central measuring system).
The lower panel shows 5 energy meters in series with a resistive load, the indoor and outdoor temperature sensors (incl. humidity) and the two pyrometers. All these devices are read out via M-Bus.

Photos: Central measuring system (framed in red) and peripheral sensors / devices





A22 List of all components (measuring system Uni Basel - in German)

ID#	Art /Sensor/Interface	Herst./Lieferant	Typ	Speisung	Verbind. zu Gerät	Ort	Koord.	Sek.-Adr./ Bemerkung
1-00	**Temp. ext.**							
1-01	Temp./Feuchte ext.	elvaco	CMa20	M-Bus	M-Bus	Da A 2L	+409	1 2 01 0101
1-02	Temp./Feuchte ext.	elvaco	CMa20	M-Bus	M-Bus	Da A 2R	+499	1 2 01 0102
2-00	**Temp. int.**							
2-01	Temp./Feuchte int.	elvaco	CMa11	M-Bus	M-Bus	Fst A	+046	1 1 01 0201
2-02	Temp./Feuchte int.	elvaco	CMa11	M-Bus	M-Bus	Abt A 1L	+107	1 1 01 0202
2-03	Temp./Feuchte int.	elvaco	CMa11	M-Bus	M-Bus	Abt A 2R	+497	1 1 01 0203
2-04	Temp./Feuchte int.	elvaco	CMa11	M-Bus	M-Bus	Abt B 1L	+507	1 1 02 0204
2-05	Temp./Feuchte int.	elvaco	CMa11	M-Bus	M-Bus	Abt B 2R	+897	1 1 02 0205
2-06	Temp./Feuchte int.	elvaco	CMa11	M-Bus	M-Bus	Fst B	+956	1 1 02 0206
3-00	**Spez. Sensoren int.**							
3-02	Kohlendioxyd CO2	Scanntronik		+24V	10-11	AbtAEcL	+247	3 1 01 0302
3-03	Kohlendioxyd CO2	Scanntronik		+24V	10-11	AbtBEcR	+757	Beckhoff 10-25 1
4-00	**Spez. Sensoren ext.**							
4-01	Solareinstrahlung von Links	Kipp & Zonen	SP Lite2	von 4-02	4-02	Da A 1L	+119	3 1 01 0401
4-02	Messverstärker	Kipp & Zonen	Ampbox	von 10-12	10-06	A DR 1L	+107	inkl. Kabel grau 7m
4-03	Solareinstrahlung von rechts	Kipp & Zonen	SP Lite2	von 4-04	4-04	Da A 1R	+189	3 1 01 0403
4-04	Messverstärker	Kipp & Zonen	Ampbox	von 10-12	10-06	A DR 1L	+107	inkl. Kabel grau 7m
5-00	**Spez. Sensoren**							
5-01	GPS Empfänger	u-blox	EVK-6H	von USB	10-01/04	A DR 1R	+197	vorhanden
10-00	**Datenerfassung, Kommunikation und M-Bus Komponenten**							
10-01	Kombi-Fensterantenne (GSM/GPS)	CELPHONE	60605004	von GPS	5-01/10-04	Fst A	+004	Kabellänge 3.5m
	Antennenverlängerung	CELPHONE	Achtung Stecker		10-01/04 5-01	A		Kabellänge 2x 10m
10-03	Switch (Ethernet LAN_0)	Distrelec	EKI/2525	+24V	Ethernet	A DR 1R	+197	5 Kanäle
10-04	Messcomputer: advantech e3m-box	Opit	S-Nr.: HEJA00004	+24V	5-01 10-03/05	A DR 1R	+197	
10-05	M-Bus Interface: PW60	RELAY	MR004C	+24V	10-05 M-Bus	A DR 1R	+197	
10-06	4-fach M-Bus A/D Wandler	RELAY	MBANDI4	+24V	3-02-03 4-01/02	A DR 1R	+197	
10-10	Beckhoff Controller	Pi-System	CX8091	+24V-BH	Ethernet	A DR 1R	+197	
10-11	Beckhoff Klemme: 2x -10..10V	Pi-System	KL3132	von 10-10		A DR 1R	+197	
10-12	Beckhoff Klemme: 2x 0-10V	Pi-System	KL3162	von 10-10		A DR 1R	+197	
10-13	Beckhoff Klemme: 2x 0-10V	Pi-System	KL3162	von 10-10		A DR 1R	+197	
10-14	Beckhoff Klemme: 2x 0-10V	Pi-System	KL3162	von 10-10		A DR 1R	+197	
10-15	Beckhoff Klemme: 2x 0-10V	Pi-System	KL3162	von 10-10		A DR 1R	+197	
10-16	Beckhoff Klemme: 4x Dig IN 24V	Pi-System	KL1104	von 10-10	Türautomat	A DR 1R	+197	
10-17	Beckhoff Klemme: 4x Dig IN 24V	Pi-System	KL1104	von 10-10	Türautomat	A DR 1R	+197	
10-18	Beckhoff Endklemme	Pi-System	KL9010	von 10-10		A DR 1R	+197	
10-20	Beckhoff Buskoppler	Pi-System	BK9100	+24V-BH	Ethernet	B DR 2R	+897	
10-21	Beckhoff Klemme: 2x -10..10V	Pi-System	KL3132	von 10-20		B DR 2R	+897	
10-22	Beckhoff Klemme: 2x 0-10V	Pi-System	KL3162	von 10-20		B DR 2R	+897	
10-24	Beckhoff Klemme: 2x 0-10V	Pi-System	KL3162	von 10-20		B DR 2R	+897	
10-25	Beckhoff Klemme: 2x 0-10V	Pi-System	KL3162	von 10-20		B DR 2R	+897	
10-26	Beckhoff Klemme: 4x Dig IN 24V	Pi-System	KL1104	von 10-20	Türautomat	B DR 2R	+897	
10-27	Beckhoff Klemme: 4x Dig IN 24V	Pi-System	KL1104	von 10-20	Türautomat	B DR 2R	+897	
10-28	Beckhoff Endklemme	Pi-System	KL9010	von 10-20		B DR 2R	+897	
11-00	**Speisung**							
11-01	DC/DC Wandler 24V zu 24V/6.25A	power-one	24RCM150-24D	150W	11-04/05	A DR 1R	+197	+24V DC-BH Supply
11-04	Batterierelais: <22.0V=AUS	UniBasel	BattRelais	FET neu!	Batterie	A DR 1R	+197	Batterieschutz
11-05	Zeitrelais: 30s Einschaltverzög.	Finder/Dist.	Finder 95.05		11-04	A DR 1R	+197	+24V DC Supply
MA/B-nm	**DC Spannungs- und Stromwandler**							
MA-01	Stromwandler: 100A zu 10V	Chen Yang	CYHCT-L20K- U100A-84	+24V	10-11 1	A SA	+035	I_BNU
MA-02	Stromwandler: ±1250A zu ±10V	LEM+LEMPower	Hat 500S	±15V	10-11 2	A Bo 2L	+310	I Mot A
MA-03	Stromwandler: 5A zu 10V	Chen Yang	CYCT03-84S3- 1.0-5A	+24V	10-12 1	A SA	+035	I_Heiz_Fst_A
MA-04	Stromwandler: 30A zu 10V	Chen Yang	CYHCT-L20K- U30A-84	+24V	10-12 2	A SA	+035	I_Heiz_Abt_A
MA-05	Spannungswandler: 30V zu 10V	SENECA	K 109UI	+24V	10-13 1	A Bo 2L	+310	U Batt 1
MA-06	Stromwandler: 300A zu 10V	Chen Yang	CYHCT-L20K- U300A-84	+24V	10-13 2	A Bo 2R	+380	I_Batt_1
MA-07	Spannungswandler: 30V zu 10V	SENECA	K 109UI	+24V	10-14 1	A SA	+035	U Batt 2
MA-08	Spannungswandler: ±100mV zu ±10V	SENECA	K 109LV	+24V	10-14 2	A SA	+035	I Batt (via Shunt)
MA-09	Stromwandler: 30A zu 10V	Chen Yang	CYHCT-L20K- U30A-84	+24V	10-15_1	A SA	+035	I_Lüft_Fst_A
MA-10	Stromwandler: 30A zu 10V	Chen Yang	CYHCT-L20K- U30A-84	+24V	10-15 2	A SA	+035	I_Info
MB-01	Stromwandler: ±2500A zu ±10V	LEM+LEMPower	Hat 1000S	+24V	10-21 1	B Da 1L	+528	I OL
MB-02	Stromwandler: ±1250A zu ±10V	LEM+LEMPower	Hat 500S	±15V	10-21 2	B Bo 1L	+610	I Mot B
MB-03 1	U-Wandler OL 1: 1500V zu 75mA	LEM	AV 100-1000	+24V	MB-03 2	B Bo 1L	+610	Spannung Oberleitung
MB-03 2	U-Wandler OL 2: 75mA zu 1.5V	Uni Basel	in DIN-Box	passiv	10-22 1	B Bo 1L	+610	U OL (20R + Zener D.)
MB-04	Stromwandler: 5A zu 10V	Chen Yang	CYCT03-84S3- 1.0-5A	+24V	10-22 2	B SB	+965	I_Heiz_Fst_B
MB-05	Stromwandler: 30A zu 10V	Chen Yang	CYHCT-L20K- U30A-84	+24V	10-23 1	B SB	+965	I_Heiz_Abt_B
MB-06	Stromwandler: 30A zu 10V	Chen Yang	CYHCT-L20K- U30A-84	+24V	10-23 2	B SB	+965	I_Lüft_Fst_B
MB-07	Stromwandler: 30A zu 10V	Chen Yang	CYHCT-L20K- U30A-84	+24V	10-24 1	B SB	+965	I_SBel_Fst_B
MB-08	Stromwandler: 30A zu 10V	Chen Yang	CYHCT-L20K- U30A-84	+24V	10-24 1	B SB	+965	I_Bel_Abt_B
Zx-nm	**DIZ Energiezähler**							
Z1-01	3 Leiter Energiezähler 230V/50Hz	EMH / ELKO	DIZ D680Mi		M-Bus	A Bo 2L	+310	E BNU out 91 01 1011
Z2-01	3 Leiter Energiezähler 230V/50Hz	EMH / ELKO	DIZ D680Mi		M-Bus	A SA	+035	E Kühl Fst A 91 01 2011
Z2-02	3 Leiter Energiezähler 230V/50Hz	EMH / ELKO	DIZ D680Mi		M-Bus	B SB	+965	E Kühl Fst B 91 02 2011
Z3-01	3 Leiter Energiezähler 230V/50Hz	EMH / ELKO	DIZ D680Mi		M-Bus	A SA	+035	E Lüft AT Abt A 91 01 3011
Z3-02	3 Leiter Energiezähler 230V/50Hz	EMH / ELKO	DIZ D680Mi		M-Bus	B SB	+965	E Lüft AT Abt B 91 02 3021