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Evaluation of potentials for Infineon SiC-MOSFETs in automotive inverter applications

Part 2
Drive-Cycle Efficiency

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1 Introduction

Siliciumcarbide (SiC) MOSFETs offer potentials due to their significantly reduced losses, their suitability for highest junction temperatures (perspectively > 200°C) and their fast switching capability in comparison to silicium-based IGBTs and MOSFETs. Within the first part of this study, several parameter variations have been carried out (switching frequency, DC-link voltage etc.) for static operating points. The investigations confirmed the potential of SiC for efficient, compact and fast-switching inverter power-stages for automotive applications like high-voltage traction-drives and auxiliary-components.

Especially for high-speed applications, like electric turbochargers or high-speed traction-drives with their need for higher switching frequencies f_{SW}, significant benefits on the system levels can be achieved due to the reduced dynamic losses (e.g. smaller required chip area per switch). Different price scenarios have been considered to have a first identification also of the economic potentials for different applications.

For a more profound evaluation of the pros and cons of the use of SiC MOSFETs in inverter applications, transient operation with realistic load profiles has to be examined. Within this second part of the study, a simulative drive-cycle analysis for automotive inverters is carried out to compare the performance of SiC MOSFET inverters with IGBT-based systems according state-of-the-art. Therefore the inverter systems are implemented in a Matlab Simulink vehicle model and different drive-cycles are examined.

In chapter 2, the basics for the simulative system modelling are given. The configurations of the different inverter systems (e.g. IGBT- and SiC-MOSFET-based) are described in chapter 3. A drive-cycle analysis for a 60 kW traction system is carried out in chapter 4 with focus on system efficiency and chip temperature behavior. Chapter 5 summarizes the investigations for a 120 kW traction drive. A summary and conclusion of the results is given in the final chapter 6.

2 System modeling

Within this chapter, the basics for the simulation of the electric drivetrain with different inverter setups are explained. The implementation of the simulation model is realized in Matlab Simulink using analytic and map-based models for all components of the electric drivetrain (e.g. inverter and electric machine). With the input of normalized or measured drive-cycles, the speed and torque demands for the electric machine and the resulting output parameters of the inverter system are calculated depending on the vehicle parameters. With implemented loss-models for each component of the drivetrain, the overall cycle-efficiency can be obtained for varying system setups and system parameters.

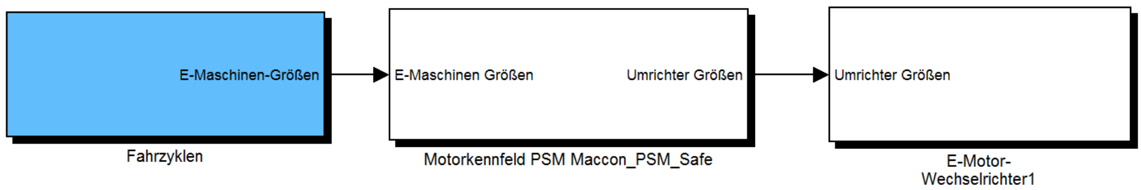

Figure 1: Matlab Simulink simulation model of the electric drivetrain

As for the first part of the study, the Volkswagen e-Golf is chosen as reference vehicle for the further investigation. The vehicle parameters are listed in Table 1.

Table 1: Vehicle parameters Volkswagen e-Golf

Vehicle	
Weight	1585 kg
Payload	150 kg
Aerodynamic resistance (cw*A)	0,7
Gear reduction	7:1

Electric machine	
Motor	PSM
Power	85 kW
Torque	270 Nm
Max. speed	12000 1/min
Traction Battery	
Cell configuration	88S3P
Energy content	24,2 kWh
Nominal voltage	323 V

For an improved comparability of the results, the DC-link voltage is set constant to 400 V for 650 V / 750 V semiconductor devices and to 800 V for inverters using 1200 V devices. This corresponds to a vehicle system setup with a (non-isolating) traction DC/DC converter between the battery system and the inverter which stabilizes the DC-link voltage.

2.1 Inverter system

The aim of the study is to compare the performance of different inverter technologies with the focus on the drive-cycle efficiency and the resulting chip temperatures. Therefore different inverter setups, using the common B6 topology, are used for the analysis. As transistors, 1200 V SiC MOSFETs and 750 V silicium IGBTs are used (the detailed configuration and technical parameters of the inverter variants are given in chapter 3). For these two types of semiconductors, the analytic models for the loss calculation, which are used within the Matlab Simulink model, are described within this chapter.

Loss calculation Si-IGBT and Si-diode

A novel calculation method from Infineon is implemented to obtain the switching and conduction losses for the silicium IGBTs and diodes. The approach uses a second order fit instead of a linear approximation for the calculation of the IGBT collector-emitter voltage (V_{CE}) and for the conduction and switching loss estimation. This leads to an improved accuracy for a broader range of the operational area of the powermodule. The influence of different junction-temperatures and gate-voltages can also be taken into account.

The conduction $P_{S,cond}$ and switching losses $P_{S,sw}$ are calculated using the following formulas (valid for IGBTs and diodes):

$$P_{S,cond} = \frac{K\hat{I}}{4\pi} \cdot \left(\frac{4a\hat{I}^2}{3} + \frac{b\pi\hat{I}}{2} + 2c + \frac{3\pi ma\hat{I}^2 \cos\varphi}{8} + \frac{4mb\hat{I}\ \cos\varphi}{3} + \frac{\pi mc\cos\varphi}{2} \right) \quad (2.1)$$

$$P_{S,sw} = f_{sw} \cdot \left(\frac{a\hat{I}^2}{4} + \frac{b\hat{I}}{\pi} + \frac{c}{2} \right) \cdot K \quad (2.2)$$

with

f_{sw}	=	Inverter switching frequency
$\hat{I}$	=	Peak value of the inverter output current
m	=	Modulation index
cos φ	=	Power factor

The 9 parameters ‚a‘ to ‚l‘ are obtained from a curve fitting procedure and have been provided from Infineon for the actual application HybridPACK Drive. Depending on the junction temperature T_j and the gate-voltage V_{GE}, the factor K is calculated according to:

$$K = \left(dT_j^2 + eT_j + f\right) \cdot \left(gV_{GE}^2 + hV_{GE} + l\right) \qquad (2.3)$$

Loss calculation SiC MOSFETs

Parameters for the second-order loss model have not yet been available for the Infineon SiC MOSFET transistors. Therefore the following formulas have been used to calculate the switching and conduction losses within these semiconductors:

$$P_{MOSFET,cond} = r_M \cdot \hat{I}^2 \left(\frac{1}{8} + \frac{m \cdot \cos\varphi}{3\pi}\right) \qquad (2.4)$$

$$P_{MOSFET,SW} = \frac{f_{SW} \cdot E_{SW} \cdot \hat{I} \cdot U_{DC}}{\pi \cdot \hat{I}_0 \cdot U_0} \qquad (2.5)$$

E_{SW} defines the switching losses at a certain reference working point with the reference peak-current $\hat{I}_0$ and -voltage U_0.

Chip temperature

Especially the SiC MOSFET conduction losses strongly depend on the junction temperature due to the varying R_{DSon}. In order to consider this dependency, the junction temperature is calculated using a Foster-Network (Figure 2) which describes the transient thermal behavior of the chip based on the losses and the coolant temperature. Within the Simulink model, the calculated chip-temperature is used in the following calculation step as input parameter for the temperature-dependent chip-loss estimation.

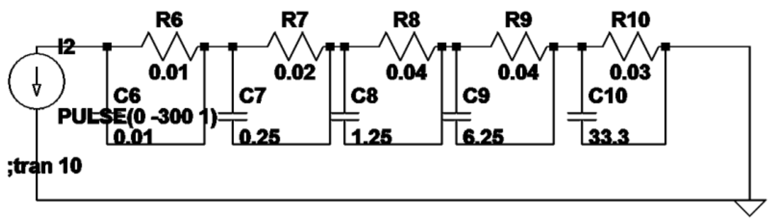

Figure 2: Foster-network

The values for the HybridPACK Drive for water-cooling have been obtained from Infineon for the IGBT and the diode (Table 2). The numbers of all resistances R (i) have been multiplied by 0,8 to get typical values (according input from Infineon).

Table 2: Foster-network parameters for the IGBT and the diode of the HybridPACK Drive

IGBT Active (Model max TDS 1.1)						
i	1	2	3	4	5	**R_{th} [K/W]**
R (i) [K/W]	0,01	0,02	0,04	0,04	0,03	**0,14**
tau (i) [s]	0,0001	0,0050	0,0500	0,2500	1,0000	

Diode Active (Model max TDS 1.1)						
i	1	2	3	4	5	**R_{th} [K/W]**
R (i) [K/W]	0,03	0,03	0,075	0,04	0,025	**0,20**
tau (i) [s]	0,0001	0,0050	0,0500	0,2500	1,0000	

For varying chip-sizes, e.g. for the SIC MOSFET inverter variants, the thermal-resistances R (i) have been scaled inverse according ‘1/x’. The time constant of every term has been left unchanged.

2.2 Electric machine

Measurement or simulation data of the original 85 kW traction motor from the Volkswagen e-Golf are not available. Therefore a PSM with close performance data and a nominal voltage of 400 V has been used for the simulation. The technical data of the machine is summarized in Table 3. By changing the number of winding-turns, the machine is adapted to the different nominal voltages used in the study.

Table 3: Technical data of simulated PSM

Nominal power	30 kW
Maximum power for 60 s	60 kW
Nominal torque	115 Nm
Maximum torque for 60 s	230 Nm
Maximum speed	10.000 rpm
Number of poles	4

Characteristic diagrams are available for all relevant machine parameters like motor-currents, phase voltages, power factor and efficiency depending on the operation point (speed/torque). Figure 3 shows exemplary the characteristic map of the motor phase current at 400 V DC-link voltage.

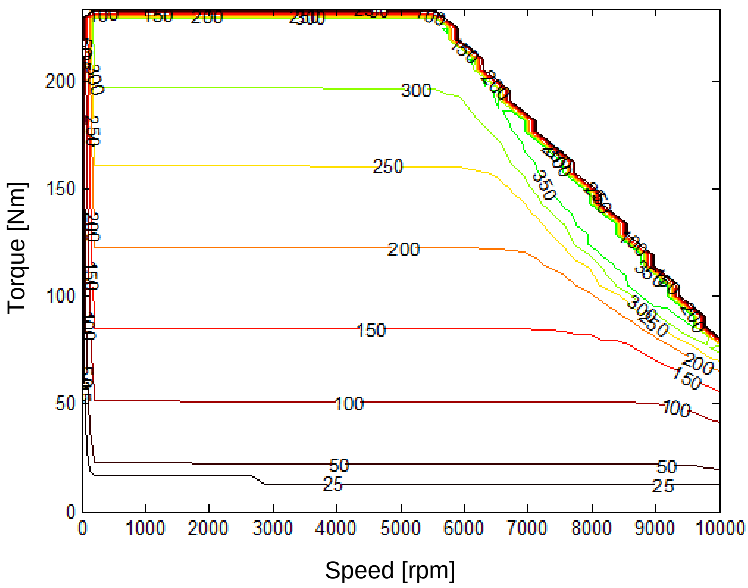

Figure 3: Characteristic map of motor phase current (60 kW PSM)

2.3 Drive-cycles

Six different drive-cycles have been used for this study to analyze the transient drivetrain behavior with varying inverter setups. As reference, the NEDC (New European Driving Cycle) and the WLTP (The Worldwide harmonized Light vehicles Test Procedures) cycle have been simulated. Due to the chosen reference vehicle Volkswagen e-Golf, the class 3 scenario of the WLTP has been used (ratio of rated power in W / kerb mass in kg > 34).

For more realistic scenarios, in total four Artemis cycles have been used which are representative for typical Jam, Urban, Road and Highway driving situations.

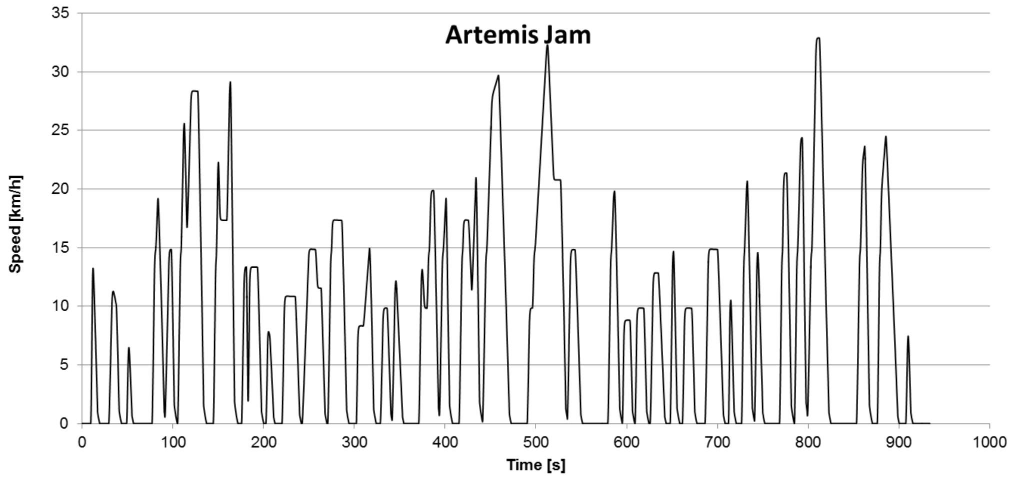

Figure 4: Artemis Jam

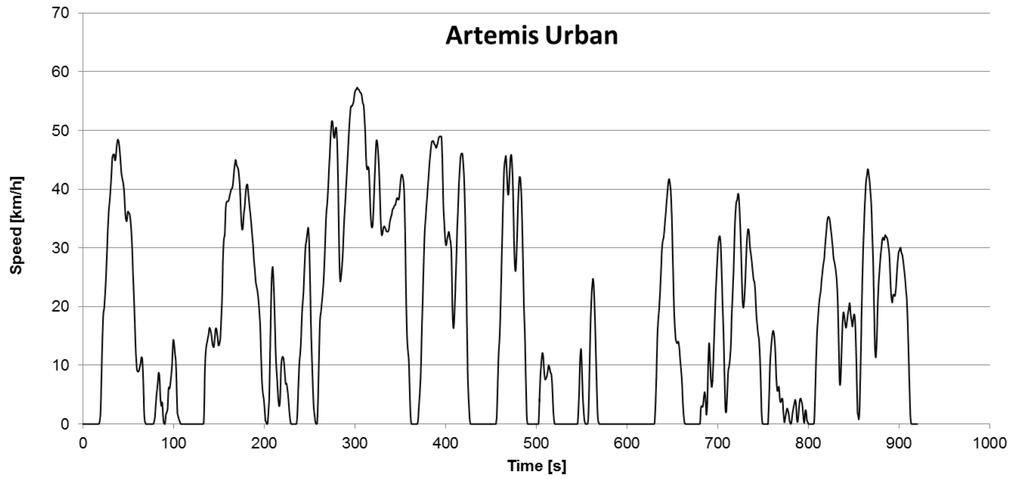

Figure 5: Artemis Urban

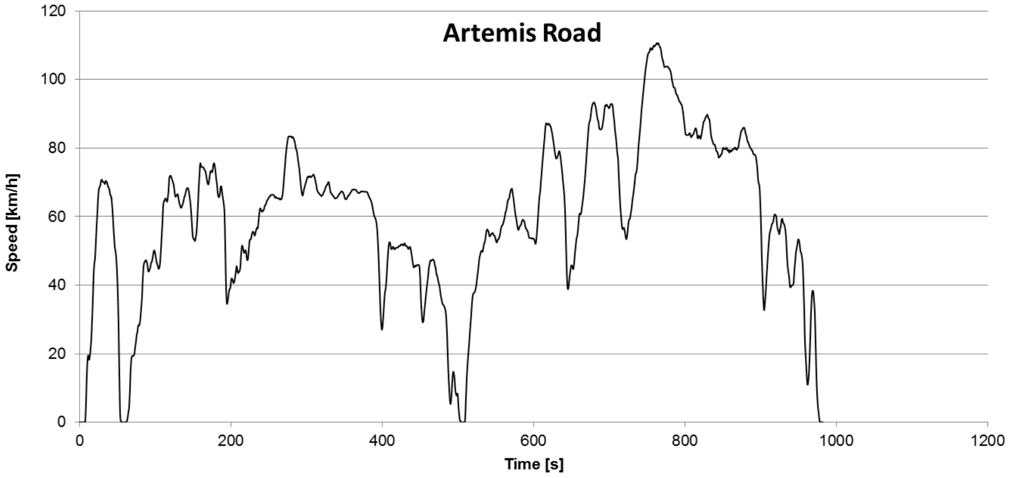

Figure 6: Artemis Road

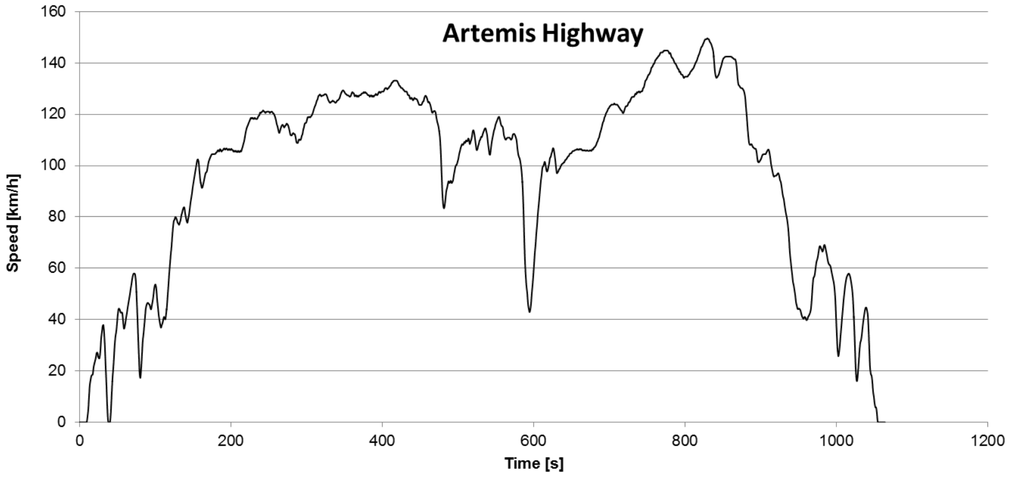

Figure 7: Artemis Highway

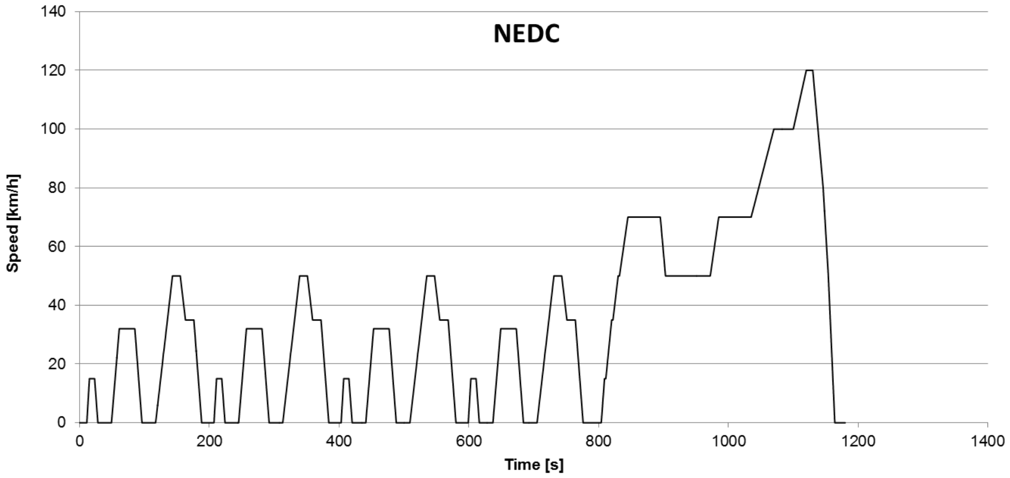

Figure 8: NEDC

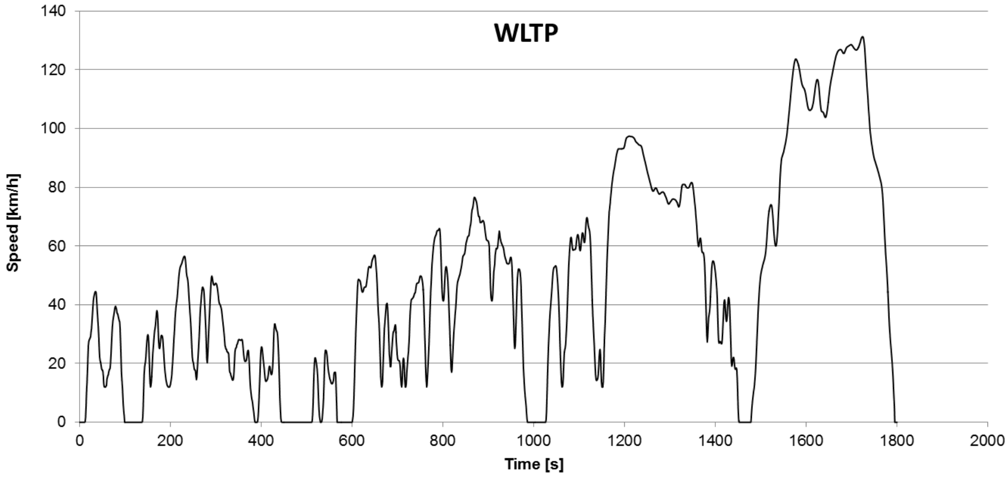

Figure 9: WLTP

3 Inverter system design

Within this chapter, the dimensioning and configuration of the analyzed inverters are explained. Three different basic inverter setups with varying semiconductors have been compared for this study:

- 1200 V SiC MOSETs
  (Based on actual Infineon development)
- HybridPACK Drive
  (750 V Si IGBTs and diodes)
- HybridPACK Drive with SiC diodes
  (750 V Si IGBTs and 650 V SiC diodes)

State of the art and benchmark for the later comparison is the actual HybridPACK Drive from Infineon which is using 750 V silicium IGBTs and also silicium diodes for the freewheeling. The evaluation of the benefits of siliciumcarbide semiconductors is carried out in two different scenarios: On the one hand, the Si diodes of the HybridPACK Drive are replaced with SiC Schottky-diodes. On the other hand, complete Full-SiC MOSFET inverters, using synchronous rectification, are simulated.

In order to see the influence on the overall system behavior, the following technical parameters have been varied:

- Switching frequency: 10 kHz, 25 kHz
- Chip active temperature hub: 40 K, 65 K
- DC-link voltage: 400 V, 800 V (SiC MOSFET only)
- Fast and slow switching (SiC MOSFET only)

Higher switching frequencies lead to higher losses in the semiconductors. Especially high-speed traction drives or auxiliary components, like electric turbochargers, or machines with limited winding-inductance may require higher switching frequencies. Otherwise the non-sinusoidal phase current with its high ripple component leads to additional losses in the electric machine or acoustic noise and torque ripple. Within the first part of this study, the suitability of SiC MOSFETs for higher switching speeds was shown due to their significantly reduced dynamic losses. Two different switching frequencies (10 kHz according state of the art and 25 kHz) are investigated in this study to identify the influence of this parameter variation on transient driving scenarios.

The acceptable active chip temperate hub is mainly limited from the used packaging- and connection-technologies. State of the art powermodules, with soldered chips and bonding as top-side chip connection, are typically operated with active temperature hubs in the range of 40 K to achieve the required automotive lifetime. New joining technologies like (double-sided) sintering and new module designs will perspectively enable higher active temperature hubs leading to higher output power per transistor or reduced required chip area for a given output power. Therefore also a temperature hub of 65 K is included in the investigation.

Current electric and hybrid vehicles are typically running with a DC-link and battery voltage in the range of 300 V to 400 V. Therefore the inverter variants using HybridPACK Drive are investigated using constant 400 V DC-link voltage. The higher blocking capability of 1200 V from the SiC MOSFETs allows higher DC-link voltages. Within this study, a DC-link voltage of 800 V is simulated. Also the number of turns of the electric machine stator winding is adapted to the higher voltages. Doubling the voltage level leads to a 50% reduction of the inverter phase currents for a constant output power.

The inverter design and dimensioning depending on the three semiconductor technologies used are described in the following three subchapters.

3.1 HybridPACK Drive

The Infineon HybridPACK Drive consists of three half-bridge powermodules (B6-topology) and represents the state-the-art for silicium- and IGBT-based automotive inverter systems (Figure 10). The powermodule has a maximum blocking voltage of V_{CES} = 750 V and a nominal current of $I_{C\ nom}$ = 660 A. A chip area of 300 mm^2 Si-IGBT and 150 mm^2 Si-diode is used per switch resulting in an overall chip area of 2700 mm^2 for the HybridPACK Drive. The temperature-dependent output characteristic is given in Figure 11.

As described in chapter 2.1, the parameters for calculating the operating-point dependent losses of the HybridPACK Drive, using the new second-order loss-model, haven been provided from Infineon.

Figure 12 shows the active temperature hub of the IGBTs of the HybridPACK Drive depending on the inverter phase current. The calculation is done using a constant specific thermal resistance of R'_{th_typ} = 0,336 K cm^2 / W. The figure indicates that the HybridPACK Drive is suitable for phase currents up to 700 A_{rms} in the case that an active temperature hub of 65 K is acceptable for the application. This value is higher than the maximum phase current of the used traction motor which is described in chapter 2.2.

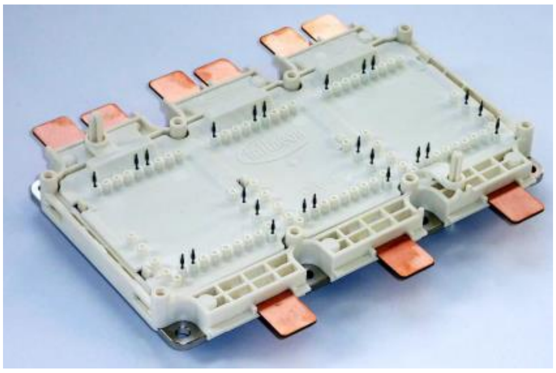

Figure 10: Infineon HybridPACK Drive

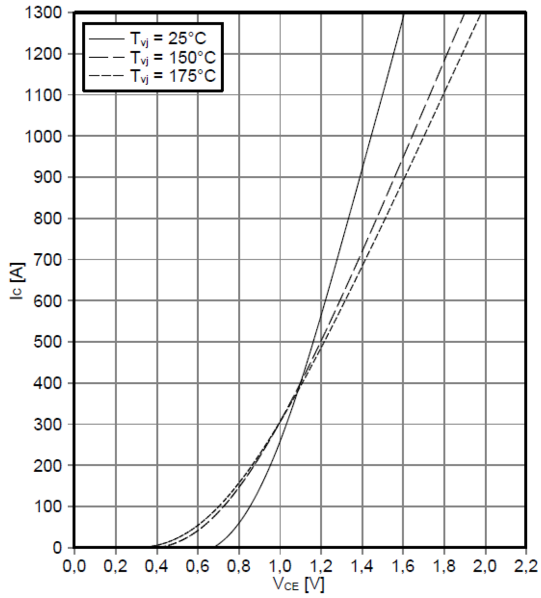

Figure 11: Output characteristic of IGBT from HybridPack Drive

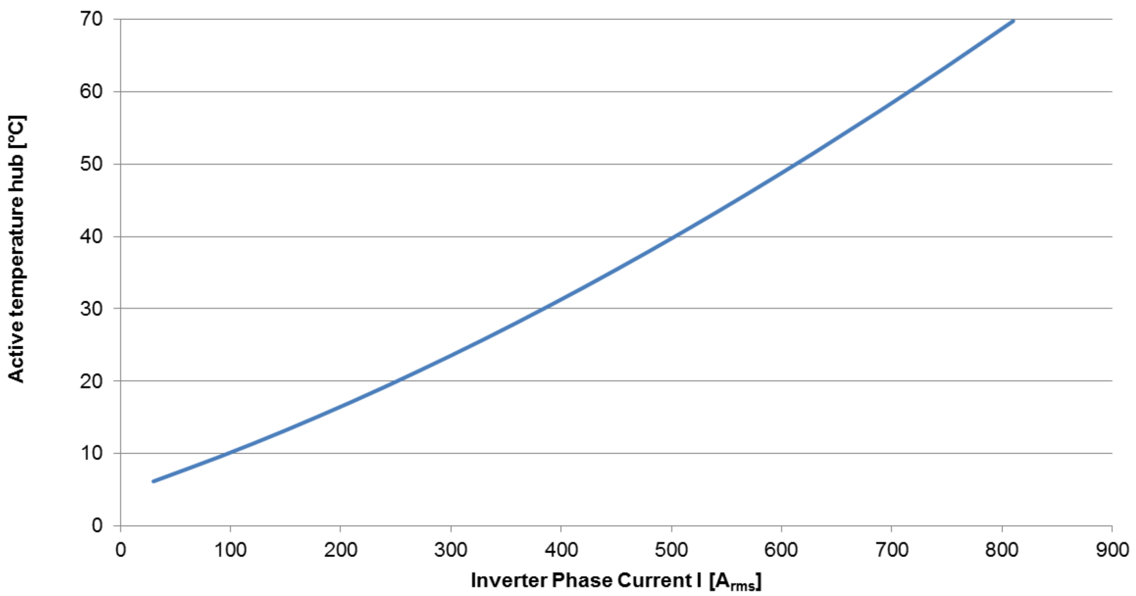

Figure 12: Chip temperature hub depending on phase current (R'_{th_typ} = 0,336 K cm^2 / W, U_{DC} = 400 V, m = 1)

3.2 HybridPACK Drive with SiC diodes

The use of SiC freewheeling Schottky-diodes with IGBTs leads to advantages regarding the switching losses. On the one hand the switching losses of the SiC Schottky-diode itself are significantly lower compared to a standard silicium diode. Due to the missing reverse recovery charge, the IGBT losses during turn on are reduced as well. This leads to a better suitability of this semiconductor combination for higher switching frequencies and therefore for example high-speed drives. Basic considerations to this topic have also been described in the first part of the study.

Within part two of the study, the use of SiC Schottky-diodes in combination with the Infineon HybridPACK Drive was investigated. As reference, the 650 V and 40 A ATV SiC G5 diode from Infineon was chosen. The temperature-dependent forward characteristic of the diode is given in Figure 13.

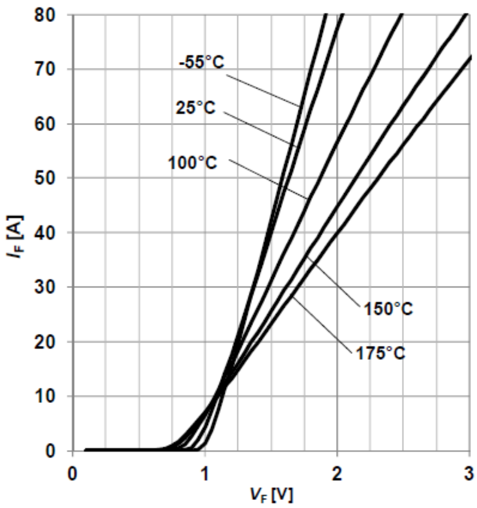

Figure 13: Forward characteristic ATV SiC G5 Diode

For comparability reasons a chip area of 150 mm^2 of SiC diode was used per switch similar to the size of the Si-diode in the original powermodule. The parameters of the original diode have been scaled linearly to this chip area. The conduction losses have been calculated using the following formula for the forward voltage V_F which was provided from Infineon.

$$V_F = V_{TH} + R_{DIFF} \cdot I_F$$
$$V_{TH}(T_j) = -0.001 \cdot T_j + 1.04[V] \qquad (3.1)$$
$$R_{DIFF}(T_j) = 3.2 \cdot 10^{-7} \cdot T_j^{\,2} + 3.2 \cdot 10^{-5} \cdot T_j + 0.012[\Omega]$$

For the calculation of the switching losses E_{rec_SiC} of the SiC diode, the value E_{rec} of the original Si-diode in the HybridPACK Drive is divided with a factor of 7 based on input from Infineon.

$$E_{rec\_SiC} = \frac{E_{rec}}{7} \qquad (3.2)$$

Due to the missing reverse recovery charge, the turn-on losses of the IGBT E_{on_SiC} with SiC diodes have been reduced by a factor of 1,5.

$$E_{on\_SiC} = \frac{E_{on}}{1{,}5} \qquad (3.3)$$

3.3 1200 V SiC MOSFETs

The chip area dimensioning of the SiC MOSFET inverters is carried out according to the procedure used in the first part of the study. Basis for the calculation are the technical values from the Infineon SiC MOSFET development summarized in Table 4.

According to the first part of the study, different scenarios for the switching speed (fast and slow) and the resulting losses have been defined. Especially for the use in drive inverter applications, the slow switching scenario with higher losses is a realistic option. The allowed voltage gradient is oftentimes limited to values in the range of 5 to 15 kV/µs due to restrictions within the electric machine (EMC, winding insulation etc.).

Table 4: Parameters of Infineon SiC MOSFET development (10 mm^2)

Parameter	Comments	min	typ	max	Unit
Drain-Source breakdown voltage	45 mOhm: V_{GS} = 0 V, I_D = 1 mA, T_j =-40	1200			V
R_{dson}	V_{GS} = 15 V, I_{Dnom}, T_j = 25C			45	mOhm
	V_{GS} = 15 V, I_{Dnom}, T_j = 150C			68	mOhm
I_{dnom}			22		A
Active area			7,76		mm^2
Gate threshold voltage	I_D = 1 mA, T_j = 25 °C, V_{GS} = V_{DS}	3,5	4,5	5,5	V
Internal gate resistance			1.5		Ohm
Body diode for-ward voltage	T_j = 25 °C, I_{Dnom}, V_{GS} = 0 V		3,5		V
Q_g	V_{DS} = 800 V, I_{dnom}, V_{GS} = 0..15 V		50		nC
E_{SW} "Fast"	V_{DS} = 700 V, 60 A, 5 Ohm		0,42		mJ
E_{SW} "Slow"	V_{DS} = 700 V, 60 A, 5 Ohm		3		mJ

Four different use cases for the SiC MOSFET inverters have been defined. The parameters of the scenarios are given in Table 5. 'Realistic' addresses a scenario with a higher DC-link voltage of 800 V. This reduces the currents for the inverter and leads to a better use of the potential of the SiC MOSFETs with their higher blocking capability. As described above, the switching speed is limited ("slow") due to the restrictions within the electric machine.

The 'Replacement' scenario descries a substitution of an existing (IGBT-)inverter running at 400 V. The DC-link voltage is not changed, therefore none of the other vehicle components (battery system, motor, DC/DC, etc.) have to be adapted or changed. The higher currents at 400 V will lead to increased losses for the SiC MOSFET inverter so that higher chip areas will be required (full potential of 1200 V SiC not used).

For the 'Worst Case' scenario the switching frequency is additionally raised to 25 kHz leading to the highest losses of all four scenarios. The use-case will allow investigating the perfor-mance of the SiC semiconductors at higher switching frequencies in comparison to the IGBT inverters. The scenario “Best Case” will indicate the performance-gain if the fast switching speed is usable for a given application at 800 V and 10 kHz leading to the lowest losses of all four scenarios.

Table 5: Scenarios for the SiC MOSFET inverter dimensioning

Variant	Parameters
Realistic	800 V, 10 kHz, slow
Replacement	400 V, 10 kHz, slow
Worst Case	400 V, 25 kHz, slow
Best Case	800 V, 10 kHz, fast

The results for the required chip area for the different scenarios (Table 6) have been obtained using the following parameters:

- P_{Motor} = 60 kW
- η_{Motor} = 85%
- cos φ = 0,5
- R'_{th} = 0,336 K cm^2 / W

The chip area sizing was carried out for the two different maximum junction temperatures of 125°C and 150°C at 85°C coolant temperature. The higher active temperature hub of 65 K reduced the required chip area in a range of ~25% for all four scenarios.

As expected, the minimum chip area was received with the “Best Case” scenario. For 65 K temperature hub a minimum SiC MOSFET surface of 320 mm^2 was required. Changing the switching speed from “fast” to “slow” – in accordance with the “Realistic” scenario – increases the required semiconductor area around 15%.

Significantly higher chip areas occur for the 400 V scenarios “Replacement” and “Worst Case”. This is mainly resulting from the higher currents required for a 400 V DC-link voltage. For the same output power twice the phase current is necessary in comparison to 800 V DC-link voltage. This underlines the necessity of higher voltages for the full use of the SiC MOSFET potential.

Table 6: Required chip area for the different scenarios

Variant	**Maximum junction temperature** *(Coolant: 85°C)*	**Chip area inverter**
Realistic	125°C	503 mm^2
	150°C	375 mm^2
Replacement	125°C	893 mm^2
	150°C	683 mm^2
Worst Case	125°C	1065 mm^2
	150°C	785 mm^2
Best Case	125°C	411 mm^2
	150°C	320 mm^2

4 Drive-cycle analysis for 60 kW drive

Based on the inverter dimensioning in chapter 3, the simulative drive-cycle analysis is described within this chapter. The overall aim is to analyze the efficiencies of the inverter systems for transient and realistic operation. For the efficiency-estimation, the following parameters and assumptions have been used:

- Efficiency for motoric operation with $T_{Machine}$ > 10 Nm, $n_{Machine}$ > 500 1/min
- Synchronous rectification for the SiC MOSFET inverters
- Basic losses: constant 150 W
  (taking the losses in other components of the inverter into account)

Table 7 shows the efficiencies for the different drive-cycles and inverter setups.

Table 7: Drive-cycle efficiencies for the different inverter setups

	Si-IGBT / Si-diodes (400 V, 10 kHz)	**Si-IGBT / SiC-diodes** (400 V, 10 kHz)	**Full SiC** (Replace-place-ment, 400 V, 125°C, 10 kHz)	**Full SiC** (Replace-ment, 400 V, 150°C, 10 kHz)	**Full SiC** (Realistic, 800 V, 125°C, 10 kHz)	**Full SiC** (Realistic, 800 V, 150°C, 10 kHz)
Chip area inverter	**2700 mm²**	**2700 mm²**	**893 mm²**	**683 mm²**	**503 mm²**	**375 mm²**
Artemis Jam	89,7 %	91,2 %	94,3 %	93,6 %	95,4 %	95,1 %
Artemis Urban	93,4 %	94,9 %	96,6 %	96,2 %	97,3 %	97,1 %
Artemis Road	96,6 %	97,1 %	98,2 %	98,0 %	98,5 %	98,4 %
Artemis Highway	98,0 %	98,4 %	99,0 %	98,9 %	99,1 %	99,1 %
NEDC	95,6 %	96,3 %	97,7 %	97,6 %	98,0 %	97,9 %
WLTP	96,5 %	97,0 %	98,2 %	98,0 %	98,4 %	98,4 %

	Full SiC (Best Case, 800 V, 125°C, 10 kHz)	**Full SiC** (Best Case, 800 V, 150°C, 10 kHz)	**Full SiC** (Worst Case, 400 V, 125°C, 25 kHz)	**Full SiC** (Worst Case, 400 V, 150°C, 25 kHz)
Chip area inverter	**411 mm²**	**320 mm²**	**1065 mm²**	**785 mm²**
Artemis Jam	96,2 %	95,9 %	92,9 %	92,3 %
Artemis Urban	97,8 %	97,6 %	95,8 %	95,4 %
Artemis Road	98,7 %	98,6 %	97,8 %	97,6 %
Artemis Highway	99,2 %	99,2 %	98,7 %	98,6 %
NEDC	98,3 %	98,2 %	97,1 %	97,0 %
WLTP	98,7 %	98,6 %	97,7 %	97,5 %

For the IGBT inverter with Si-diodes it can be summarized that the efficiency is reduced especially for urban drive-cycles with lower average traction power and a higher number of accelerations. Also the impact of the constant losses of 150 W is higher for these low-energy profiles for all inverter variants. During phases of acceleration – with their higher torque demand – the losses in the inverter are comparably higher due to the increased currents ($P \sim I^2$). Also the switching losses and the additional losses due to the IGBT knee voltage V_{CE0} are adding to the overall value. In combination with the lower average traction power, these losses lead to the reduced efficiency values for the IGBT inverter variant. For drive-cycles with higher average speed and traction power as well as more constant driving (like the Artemis Highway) the efficiency increases significantly.

The efficiencies for all compared SiC MOSFET inverters are quite close (but with strongly varying chip areas depending on the use-case). All show good performance especially for the slower drive-cycles with efficiencies improvements up to 5% compared to the HybridPACK Drive. For higher speed drive-cycles (like the Artemis Highway or Road) this advantage is reduced to ~1%.

Additional SiC Schottky diodes in combination with the IGBT transistors lead to an improvement of the efficiency especially for the slower drive-cycles. Efficiency gains of up to 1,5% can be achieved. This mainly due to the reduced switching losses for the Schottky-diode and the IGBT (see details in chapter 3).

In order to investigate the influence of higher switching frequencies, the two IGBT inverters have been simulated with 25 kHz. For increased switching frequencies, the advantage for the inverter with the SiC Schottky diodes increases as shown in Table 8. Differences of ~3% can be achieved at lower speed drive-cycles.

*Table 8: Efficiencies IGBT inverters with **25 kHz***

	Si-IGBT / Si-diodes (400 V, **25 kHz**)	**Si-IGBT / SiC-diodes** (400 V, **25 kHz**)
Chip area inverter	**2700 mm^2**	**2700 mm^2**
Artemis Jam	83,5 %	87,1 %
Artemis Urban	89,9 %	92,2 %
Artemis Road	94,3 %	95,6 %
Artemis Highway	96,7 %	97,5 %
NEDC	92,8 %	94,4 %
WLTP	94,1 %	95,5 %

Especially for the dimensioning of the inverter cooling system, the overall heat-losses for the drive-cycles are of interest. In Table 9 the summarized losses for different drive-cycles and exemplary inverter setups are shown. The SiC MOSFET inverter reduces the overall losses in a range of 60 % leading to reduced cooling effort compared to the IGBT-based HybridPACK Drive.

Table 9: Summarized inverter losses for different drive-cycles

	Si-IGBT / Si-diodes (400 V, 10 kHz)	**Full SiC** (Realistic, 800 V, 125°C, 10 kHz)
Artemis Jam	3,0 10^5 J	1,2 10^5 J
Artemis Urban	3,8 10^5 J	1,6 10^5 J
Artemis Road	4,2 10^5 J	1,8 10^5 J
Artemis Highway	5,5 10^5 J	2,4 10^5 J
NEDC	3,8 10^5 J	1,7 10^5 J
WLTP	7,2 10^5 J	3,1 10^5 J

Figure 14 to Figure 17 show exemplary temperature profiles for the SiC-MOSFET inverter (Scenario "Full SiC - Realistic 125°C") and the IGBT of the HybridPACK Drive for the Artemis Urban and the Artemis Highway drive-cycles. The coolant temperature is set to constant 85°C. The temperature profiles for the other drive-cycles are given in the appendix in chapter 7.1 and 7.2.

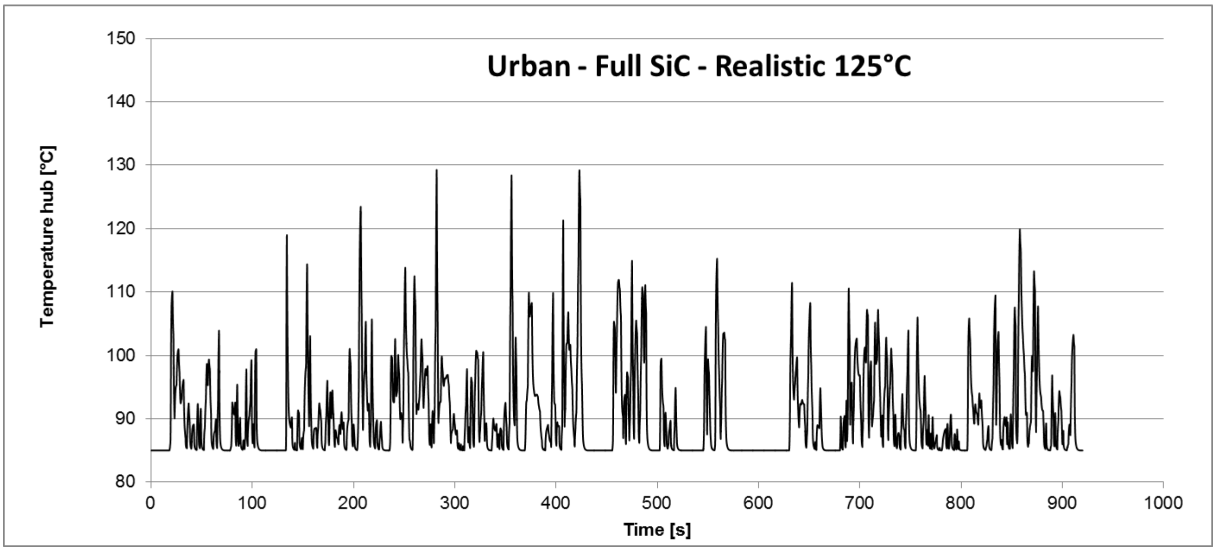

Figure 14: Temperature profile "Full SiC - Realistic 125°C" for Artemis Urban

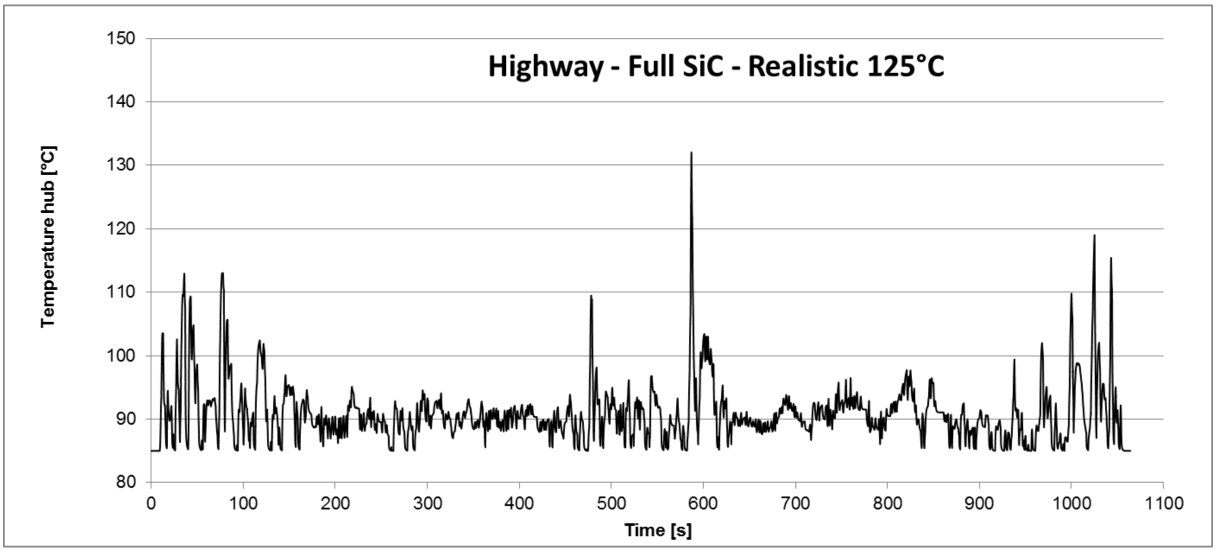

Figure 15: Temperature profile "Full SiC - Realistic 125°C" for Artemis Highway

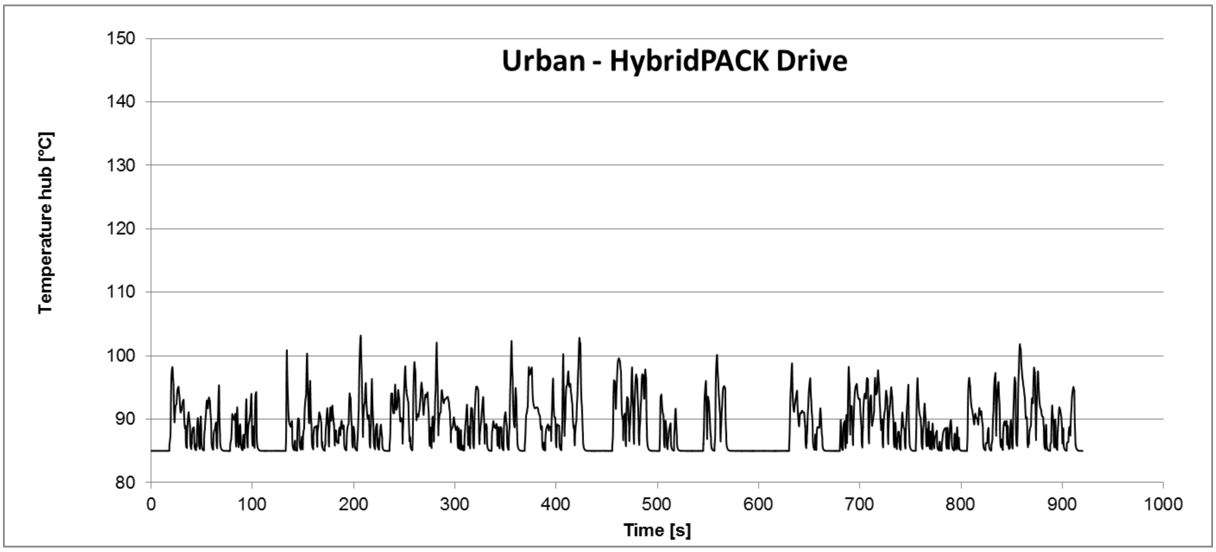

Figure 16: Temperature profile "HybridPACK Drive" for Artemis Urban

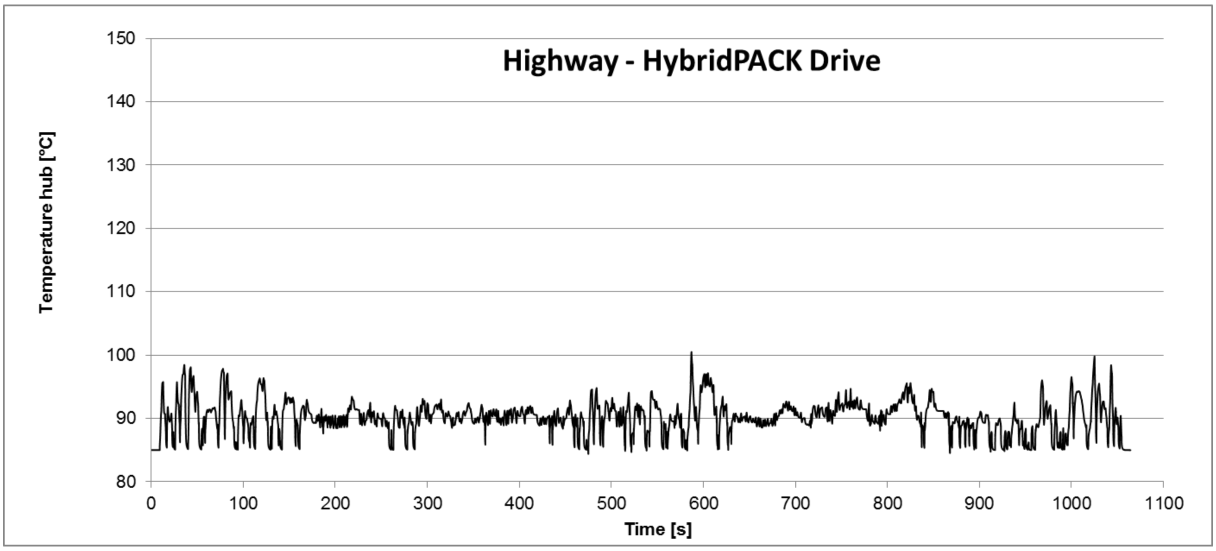

Figure 17: Temperature profile "HybridPACK Drive" for Artemis Highway

The maximum temperature values of the SiC MOSFET inverter are in a range of 130°C. The comparison of the two temperature profiles underlines the higher number of accelerations during the Artemis Urban driving scenario in comparison to the Artemis Highway leading to high current values and active temperature peaks.

It can be seen that the temperature stress on the HybridPACK Drive is comparably low. The maximum active temperature hub is in a range of 15 K and therefore significantly lower than the rated 40 K or 65 K. This can be explained due to the reduced maximum phase currents for the given drive-cycle scenarios which are in a range of 250 A_{rms}.

For a better comparison of the two technologies, a full use of the HybridPACK Drive performance is necessary. Therefore the drive-cycles are intensified in chapter 5 to increase the maximum phase currents.

5 Drive-cycle analysis for 120 kW drive

As described in chapter 4, the original drive-cycles are virtually intensified to use the full potential of the original HybridPACK Drive in terms of output current and output power. This is done using the following parameter changes in comparison to the 60 kW electric drivetrain simulated in chapter 4:

- Doubling of the electric motor traction power to 120 kW
  (scaling the parameters of the 60 kW PSM from chapter 4)
- Increasing of torque and phase-current demands during acceleration with virtually heavier vehicle (non-realistic vehicle mass)

A higher weight of the vehicle leads to higher torque demands and therefore inverter phase currents for a given acceleration within the drive-cycles. With an (non-realistic) increasing of the vehicle weight by a factor of 3, maximum inverter currents of ~700 A_{rms} are achieved for the comparison (see exemplary section of phase currents within Artemis Urban cycle in Figure 18).

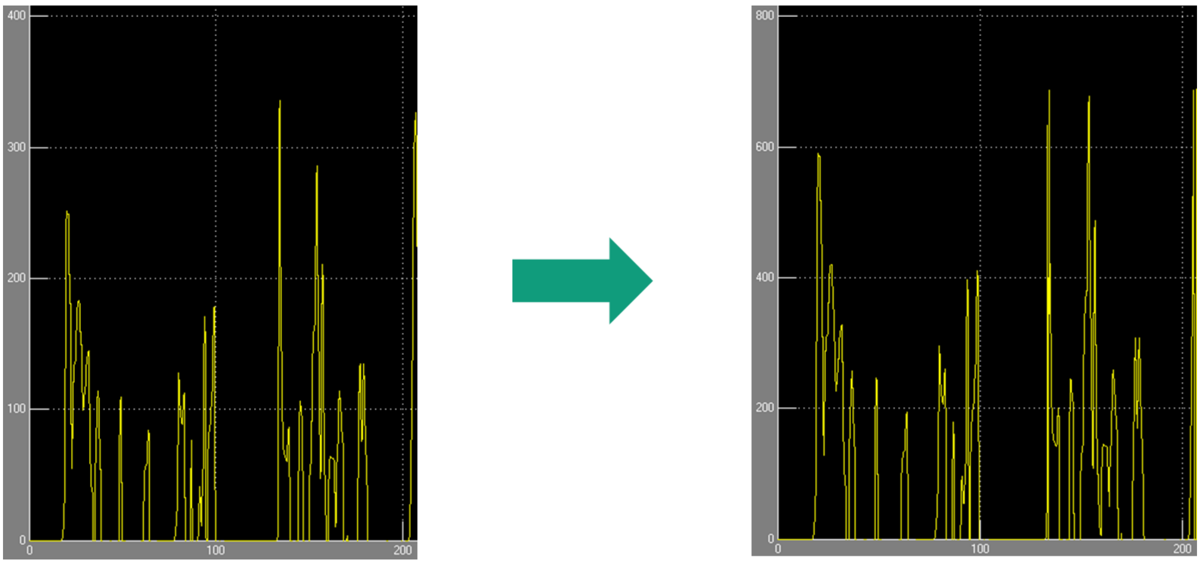

Figure 18: Current peaks during acceleration for real vehicle weight (left) and increased vehicle weight (right, factor 3)

The configuration of the IGBT-based inverter variants remains unchanged for this analysis. Due to the higher phase currents and therefore higher losses, the required chip areas for the

SiC MOSFET inverters have been recalculated (Table 10). This has been done using the following parameters

- P_{Motor} = 120 kW
- η_{Motor} = 85%
- cos φ = 0,5
- R'_{th} = 0,336 K cm^2 / W
- ΔT_{Chip} = 65 K

The required chip areas of the 120 kW SiC MOSFET inverters for the scenarios defined in chapter 3 are summarized in Table 10. As expected, the chip areas rise due to the increased output phase current of the inverter. The gap between the “Best Case” and the “Worst Case” scenario remains significant.

Table 10: Required chip area for the 120 kW SiC MOSFET inverters for different scenarios

Variant	**Parameters**	**Maximum junction temperature** *(85°C coolant temperature)*	**Chip area inverter**
Realistic	800 V, 10 kHz, slow	150°C	987 mm^2
Replacement	400 V, 10 kHz, slow	150°C	1798 mm^2
Worst Case	400 V, 25 kHz, slow	150°C	2066 mm^2
Best Case	800 V, 10 kHz, fast	150°C	844 mm^2

The resulting drive-cycle efficiencies for the changed setup with maximum 120 kW motor traction power are given in Table 11.

The general trend is equal to the 60 kW scenarios. The SiC MOSFET inverters show an improved efficiency performance for the slow-speed drive-cycles due to the reduced conduction and switching losses. The SiC diodes in combination with the IGBTs of the HybridPACK drive lead to a slight advantage also for the slower drive-cycles in a range of 1,5%.

Table 11: Drive-cycle efficiencies for the different inverter setups with 120 kW traction power

	Si-IGBT / Si-diodes (400 V, 10 kHz)	**Si-IGBT / SiC-diodes** (400 V, 10 kHz)	**Full SiC** (Realistic, 800 V, 150°C 10 kHz)	**Full SiC** (Replacement, 400 V, 150°C 10 kHz)	**Full SiC** (Worst Case, 400 V, 150°C 25 kHz)	**Full SiC** (Best Case, 800 V, 150°C 10 kHz)
Chip area inverter	**2700 mm²**	**2700 mm²**	**987 mm²**	**1798 mm²**	**2066 mm²**	**844 mm²**
Artemis Jam	91,0 %	92,8 %	96,8 %	95,4 %	94,2 %	97,5 %
Artemis Urban	94,6 %	95,8 %	98,1 %	97,2 %	96,5 %	98,5 %
Artemis Road	97,2 %	97,7 %	99,0 %	98,7 %	98,2 %	99,2 %
Artemis Highway	98,2 %	98,6 %	99,3 %	99,2 %	98,7 %	99,4 %
NEDC	96,3 %	97,0 %	98,7 %	98,3 %	97,8 %	99,0 %
WLTP	96,8 %	97,5 %	98,9 %	98,5 %	98,0 %	99,1 %

The advantages in terms of a reduction of the overall chip area with the use of SiC MOSFETs are not as significant as in chapter 4 due to the equal output power and output currents as the HybridPACK Drive inverter. The numbers are also giving an indication about price scenarios for the SiC semiconductors (e.g. Cent/mm²) that would lead to an economic break-even point.

The temperature profile for the HybridPACK Drive and the SiC-MOSFET inverter (scenario 'Realistic') are given in Figure 19 to Figure 22 for the Artemis Urban and the Artemis Highway drive-cycles. As targeted, the HybridPACK Drive is now also reaching active temperature hubs close to 65 K. The temperature profiles for the other drive-cycles are given in the appendix in chapter 7.3 and 7.4.

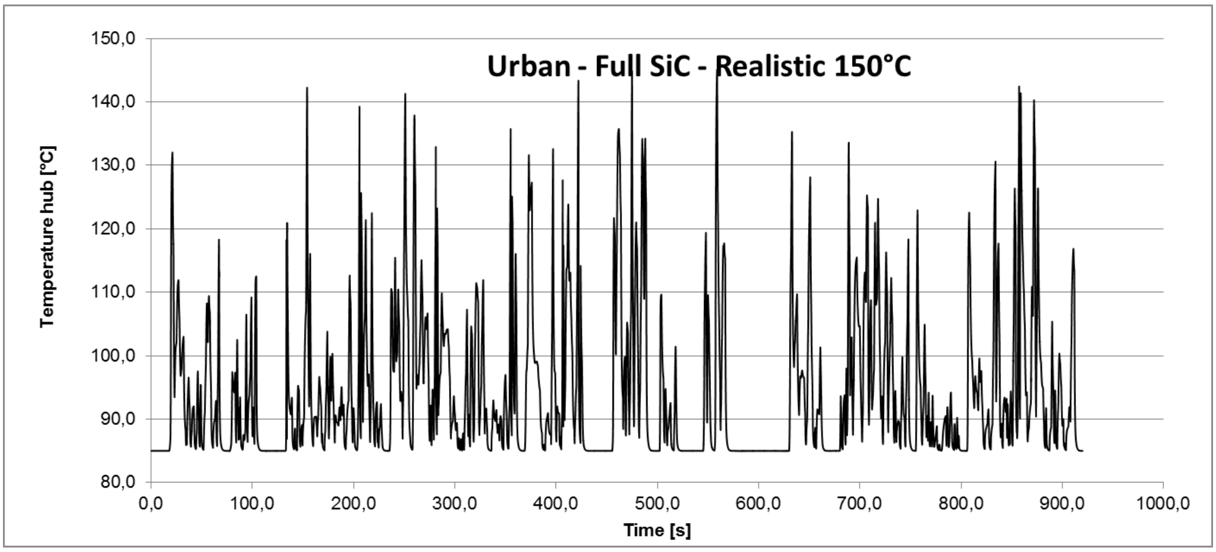

Figure 19: Temperature profile "Full SiC - Realistic 150°C" for Artemis Urban

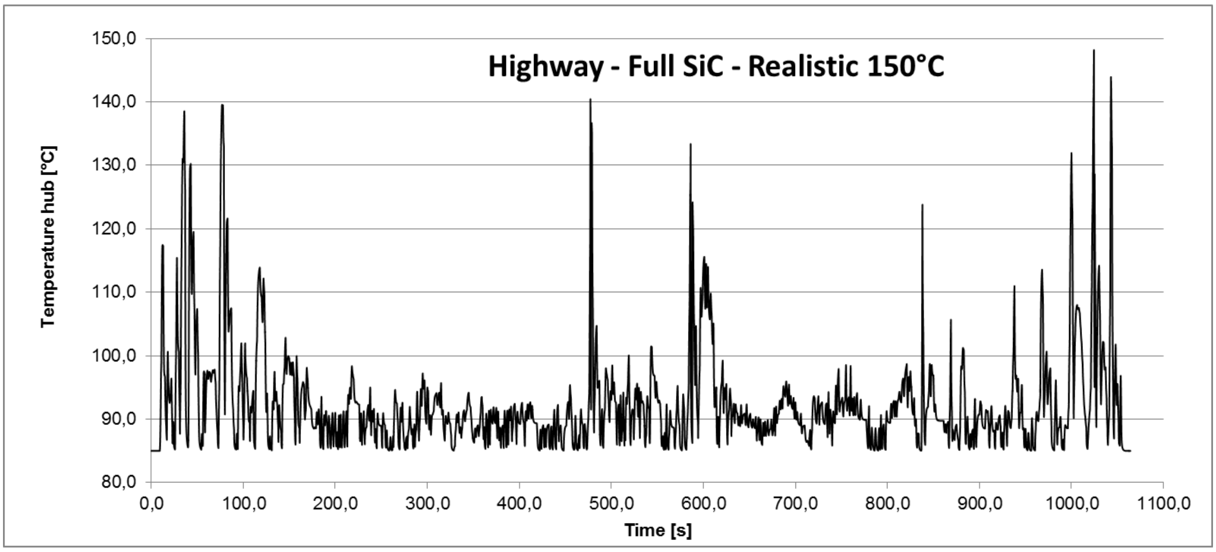

Figure 20: Temperature profile "Full SiC - Realistic 150°C" for Artemis Highway

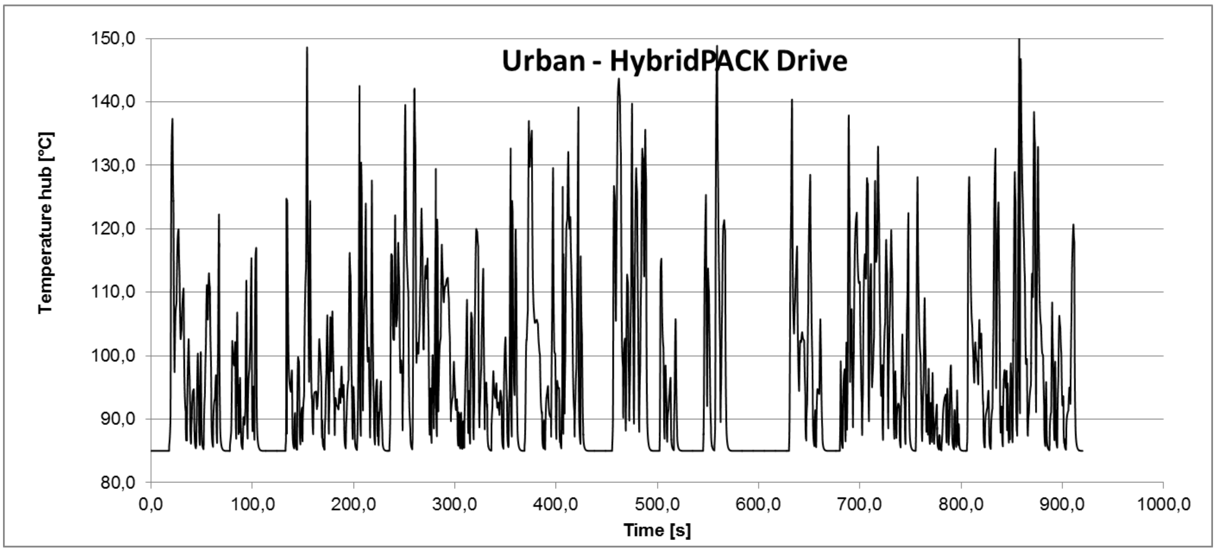

Figure 21: Temperature profile "HybridPACK Drive" for Artemis Urban

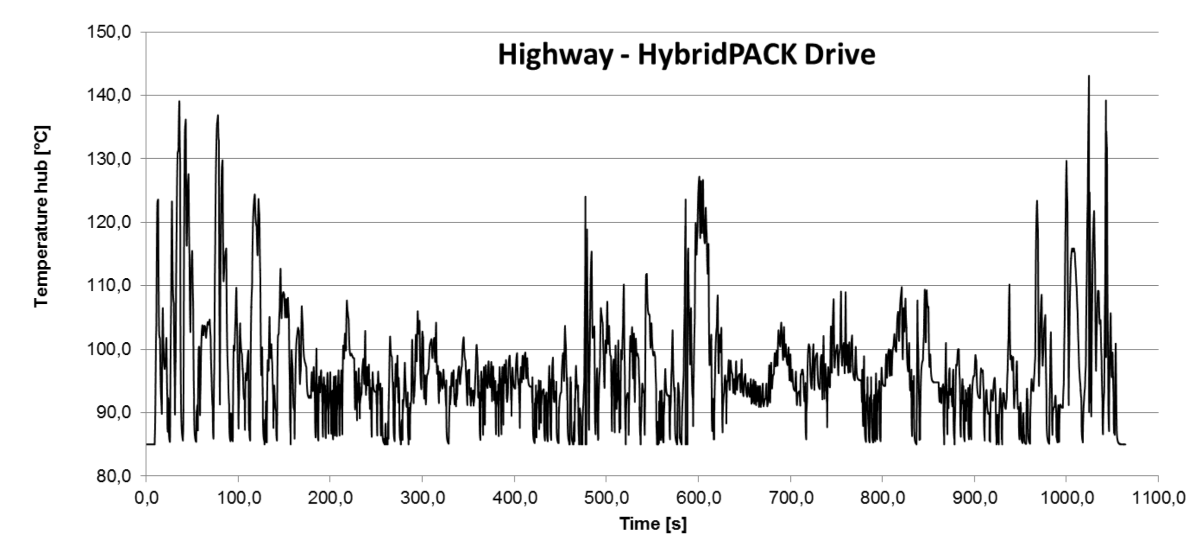

Figure 22: Temperature profile "HybridPACK Drive" for Artemis Highway

A rainflow-extraction for the chip-temperatures was performed to determine the thermo-mechanical stress induced for the different inverter variants. Table 12 summarizes the results for the HybridPACK Drive (HP) and the SiC MOSFET inverter "Full SiC - Realistic 150°C" (SiC). Active temperature hubs up to 60 K occur during the cycles (0,5 indicates half-cycles according the rainflow definition). Due to the dimensioning of the inverters to identical max. currents, the variants show similarities in their temperature behavior for different drive-cycles.

Table 12: Result of rainflow-extraction for chip temperatures

Hub	Jam		Urban		Road		Highway		NEDC		WLTC	
ΔT	**HP**	**SiC**	**HP**	**SiC**	**HP**	**SiC**	**HP**	**SiC**	**HP**	**SiC**	**HP**	**SiC**
5K	62,5	45	80	74,5	50	41	46,5	27,5	9	8	59	43
10K	8	5	10,5	4,5	4,5	2	4	3	0	0	3	2,5
15K	1	0	1,5	0,5	0	0,5	0	0,5	0	0	1	0
20K	0	0	0,5	0,5	0	0	0	0	0	0	0	0
25K	0	0	0	0	0	0	0	0	0	0	0	0
30K	0	0	0	0	0	0,5	0	0	0	0	0	0
35K	0	0	0	0	0	0	0	0	0	0	0	0
40K	0	0	0	0	0	0	0	0	0,5	0	0	0
45K	0,5	0	0	0	0	0,5	0	0,5	0	0	0	0
50K	0	0	0,5	0	0	0	0	0	0	0	0	0
55K	0	0,5	0	0	0	0	0	0	0	0,5	0	0
60K	0	0	0	0,5	0,5	0	0,5	0	0	0	0	0

6 Conclusion

The results of the second part of the study underline the findings within the first part: SiC MOSFETs enable the realization of compact and highly efficient inverter systems also for automotive applications.

For similar performance data and boundary conditions, the required chip area with SiC MOSFETs is significantly reduced in comparison to IGBT-based inverters like the Hybrid-PACK Drive. Due to the reduced chip losses, efficiency gains up to 5% can be achieved for a variety of driving scenarios. The best performance gains are obtained for slower urban drive-cycles (e.g. Artemis Jam and Urban) with a high number of accelerations and therefore high peak-currents. It was also shown that the required cooling effort on the inverter system level can be reduced using SiC-MOSFETs which potentially allows to optimize the vehicle cooling system.

Due to the reduced switching losses, the SiC MOSFET performance gains increase with higher switching frequencies also for transient operation. The use of SiC Schottky-diodes instead of Si-diodes in the HybridPACK Drive leads to efficiency advantages especially for increased switching frequencies as shown in chapter 4.

For a full use of the 1200 V SiC MOSFT potential, a higher DC-link voltage in a range of 800 V would be the optimum. This reduces the required currents for a given output power. Reduced losses and chip areas within the inverter are the result. It has to be considered that this would require significant changes of the vehicle high-voltage system and all the involved components like the traction battery.

Existing limitations for current electric machines for automotive applications have to be questioned and analyzed. It would help to further reduce the switching losses and the required chip areas of the SiC MOSFET inverters if higher voltage gradients than 5 to 15 kV/µs would be acceptable for the motor (and also for the vehicle EMC-management). For this targeted high switching speeds also low inductive commutation cells are essential.

7 Appendix

7.1 Temperature profiles 60 kW drive for SiC MOSFET

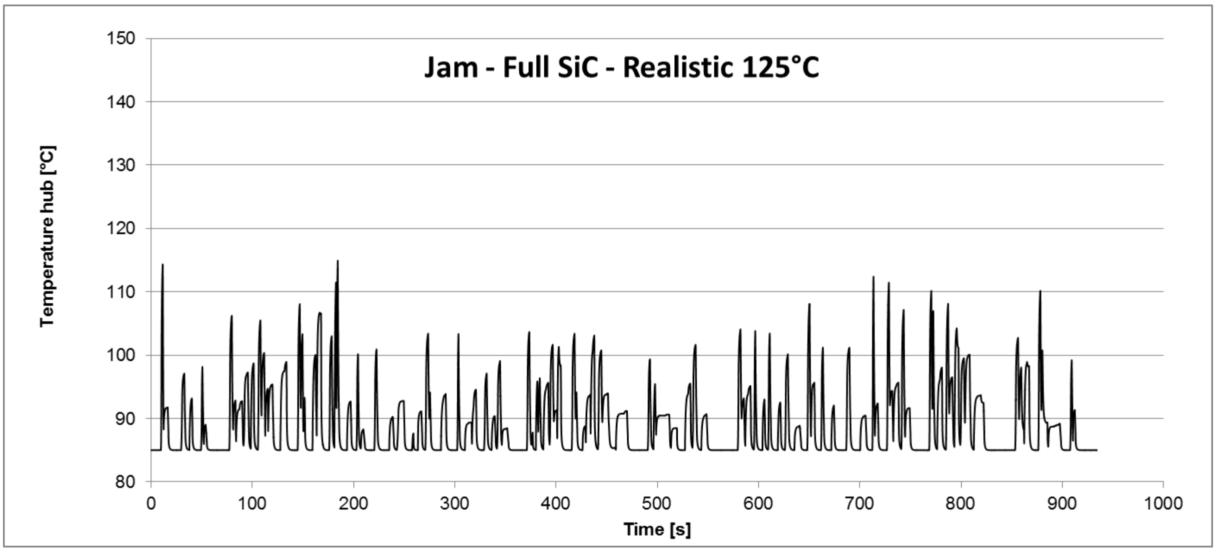

Figure 23: Temperature profile “Full SiC - Realistic 125°C” for Artemis Jam

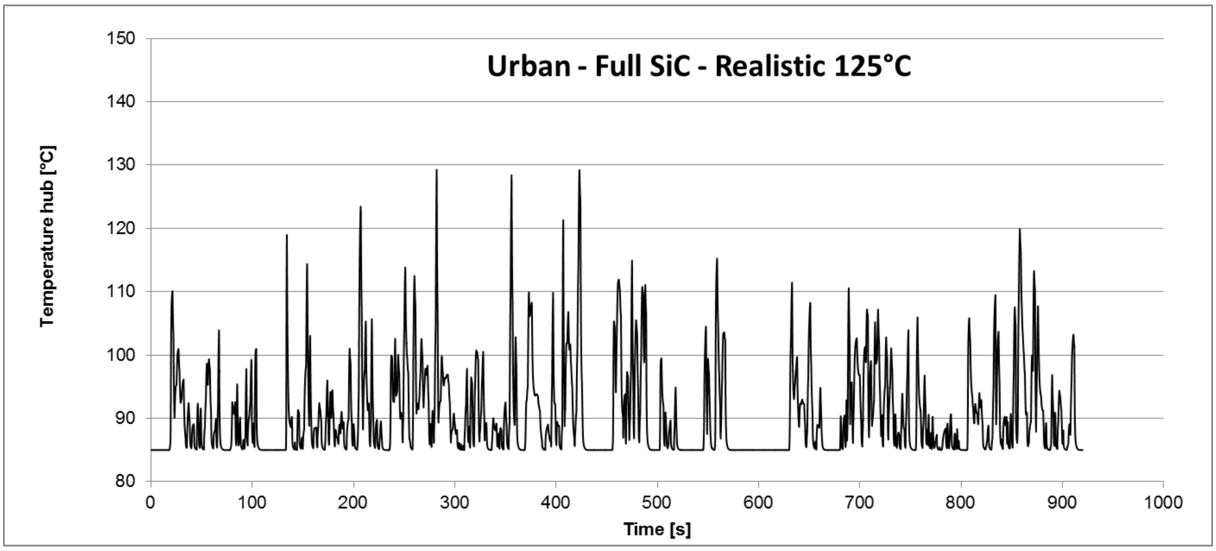

Figure 24: Temperature profile “Full SiC - Realistic 125°C” for Artemis Urban

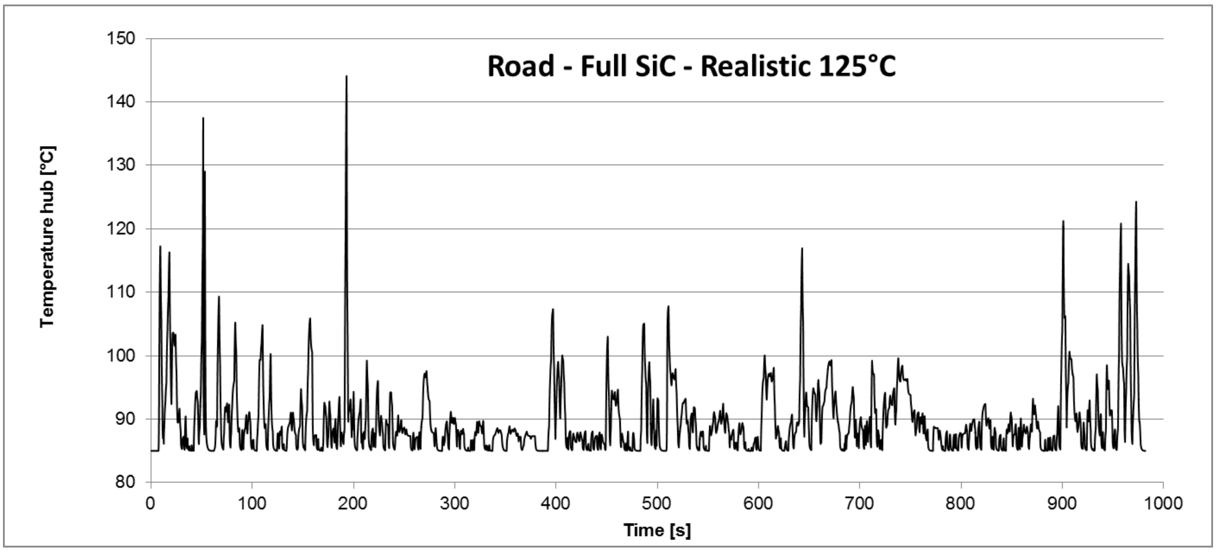

Figure 25: Temperature profile “Full SiC - Realistic 125°C” for Artemis Road

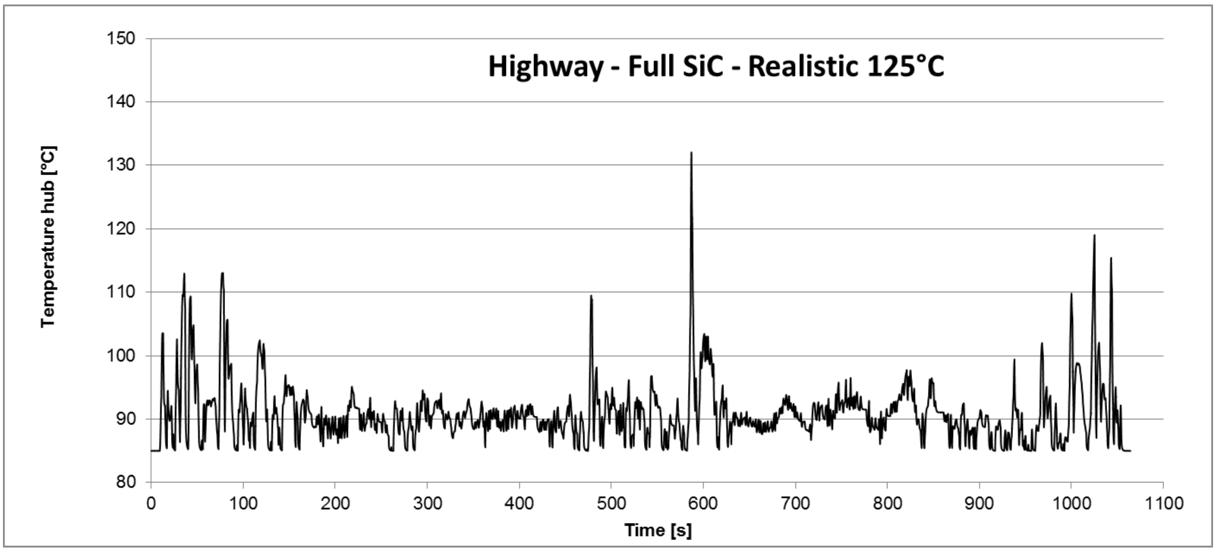

Figure 26: Temperature profile “Full SiC - Realistic 125°C” for Artemis Highway

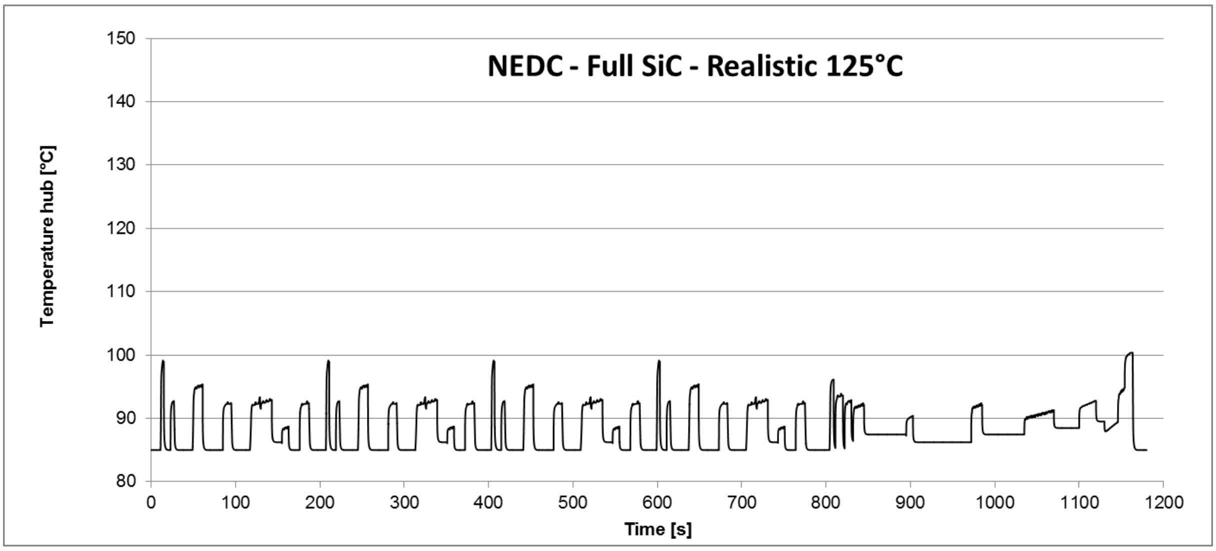

Figure 27: Temperature profile “Full SiC - Realistic 125°C” for NEDC

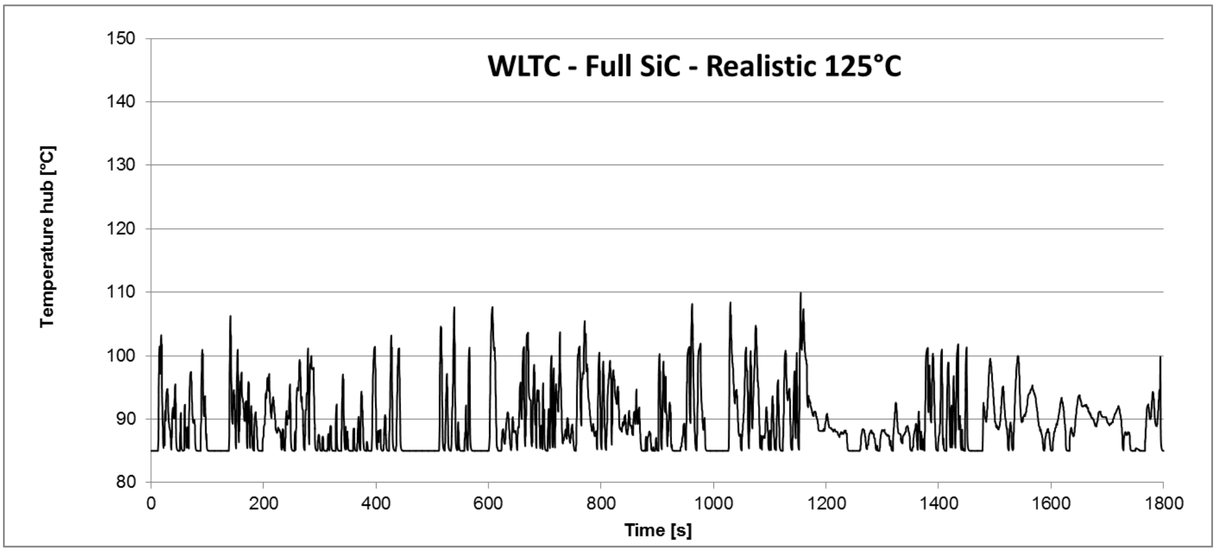

Figure 28: Temperature profile "Full SiC - Realistic 125°C" for WLTC

7.2 Temperature profiles 60 kW drive for HybridPACK Drive

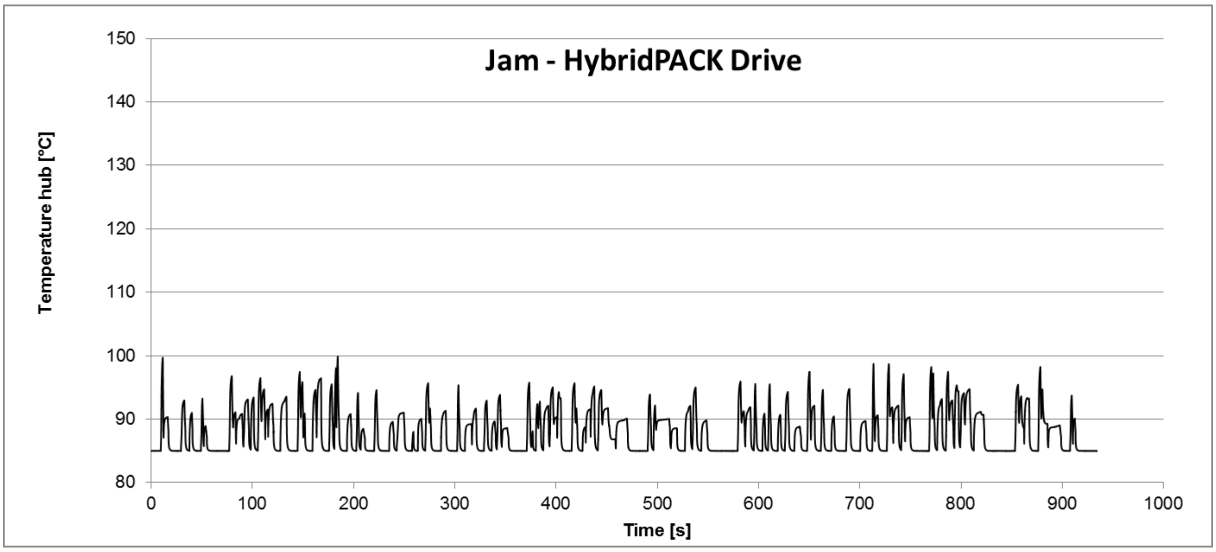

Figure 29: Temperature profile "HybridPACK Drive" for Artemis Jam

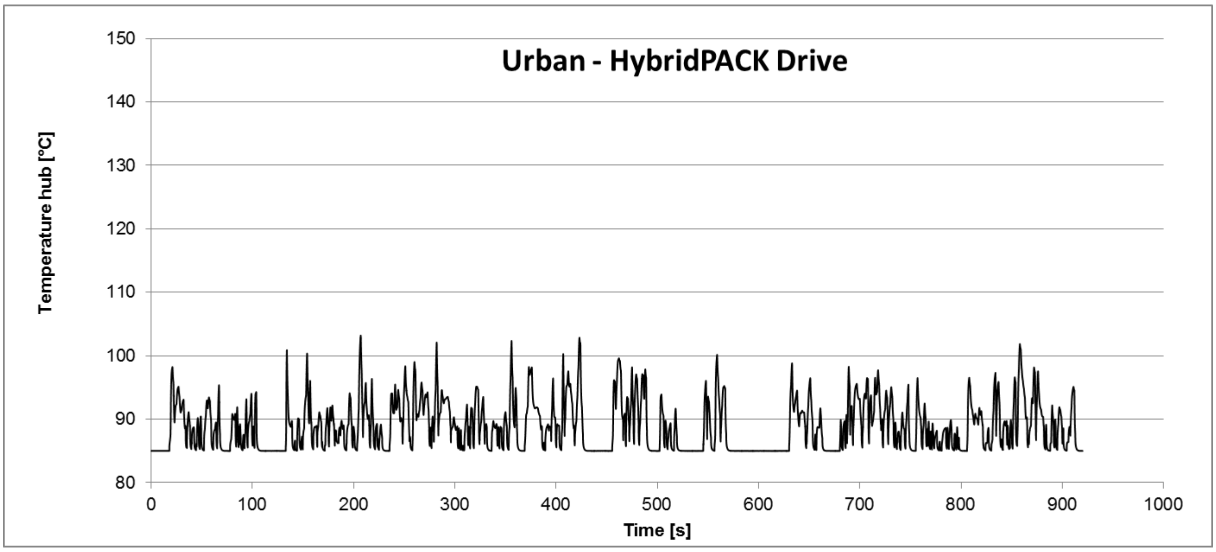

Figure 30: Temperature profile “HybridPACK Drive” for Artemis Urban

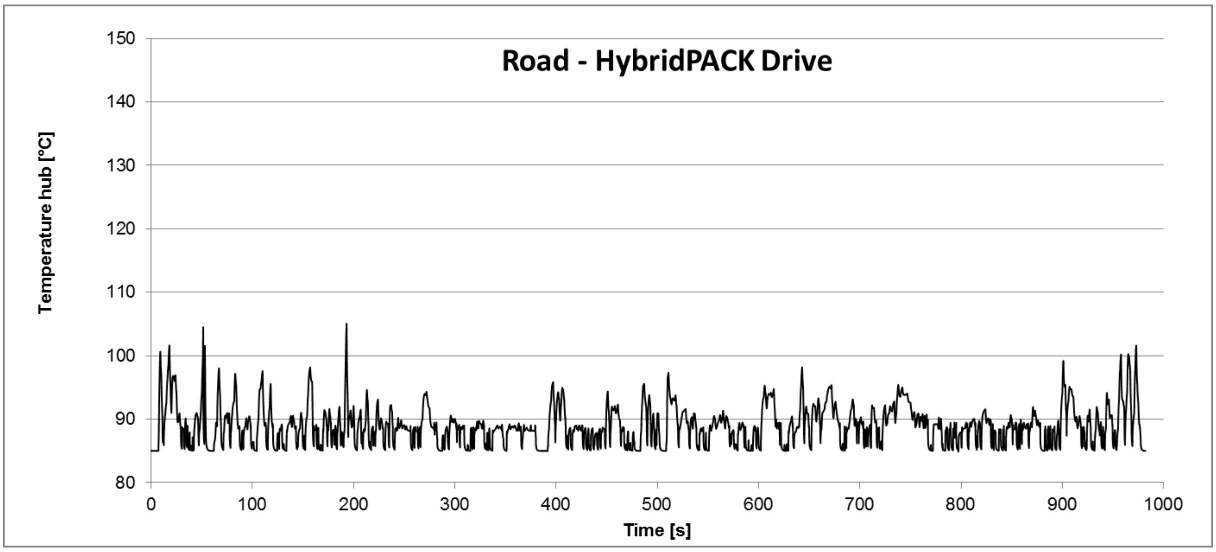

Figure 31: Temperature profile “HybridPACK Drive” for Artemis Road

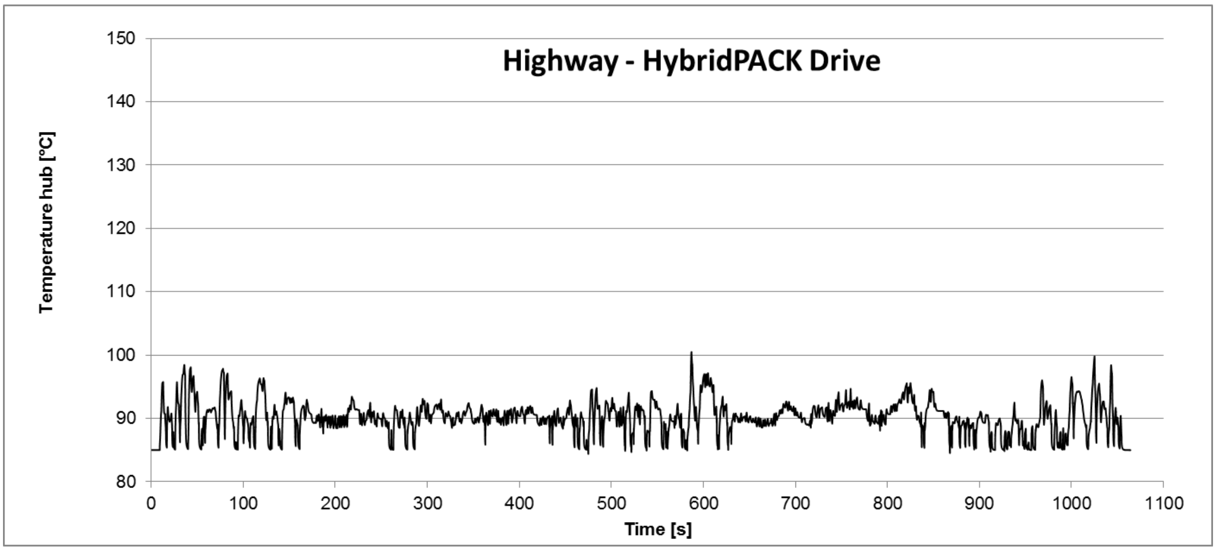

Figure 32: Temperature profile “HybridPACK Drive” for Artemis Highway

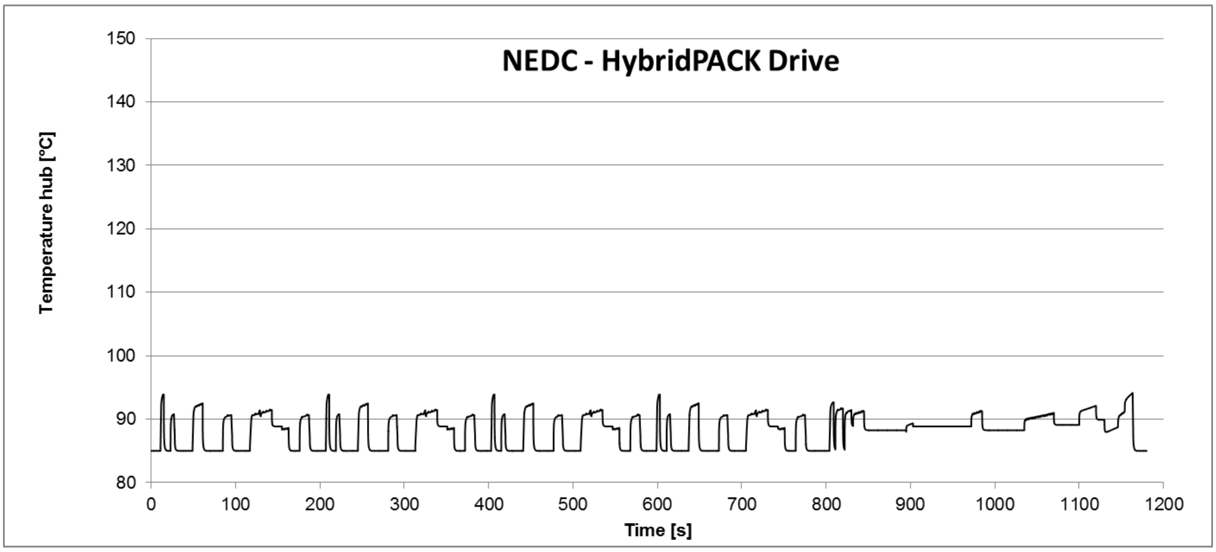

Figure 33: Temperature profile “HybridPACK Drive” for NEDC

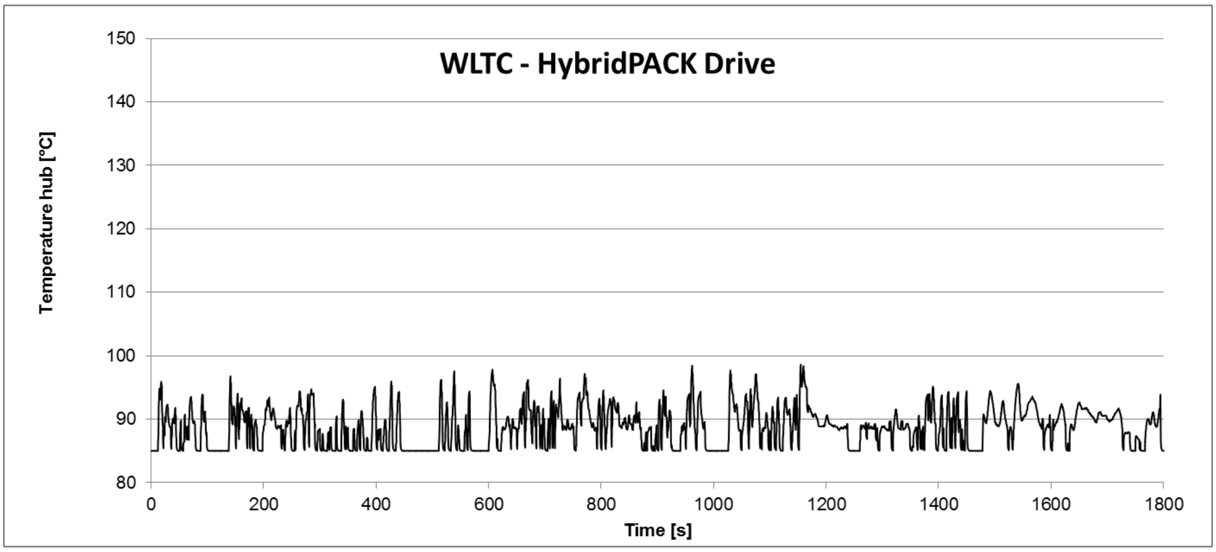

Figure 34: Temperature profile “HybridPACK Drive” for WLTC

7.3 Temperature profiles 120 kW drive for SiC MOSFET

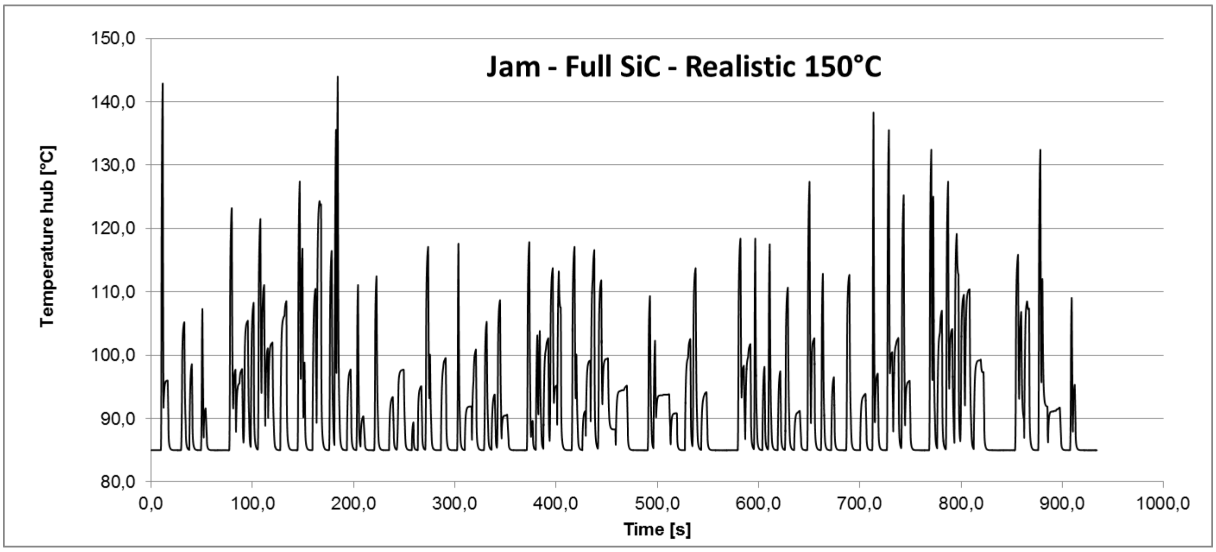

Figure 35: Temperature profile “Full SiC - Realistic 150°C” for Artemis Jam

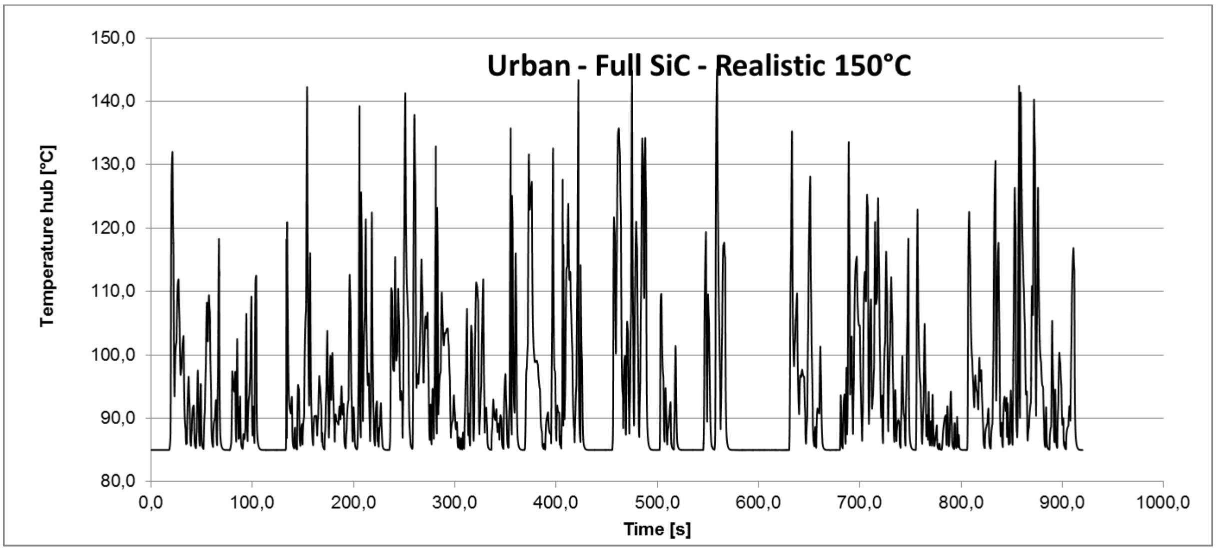

Figure 36: Temperature profile “Full SiC - Realistic 150°C” for Artemis Urban

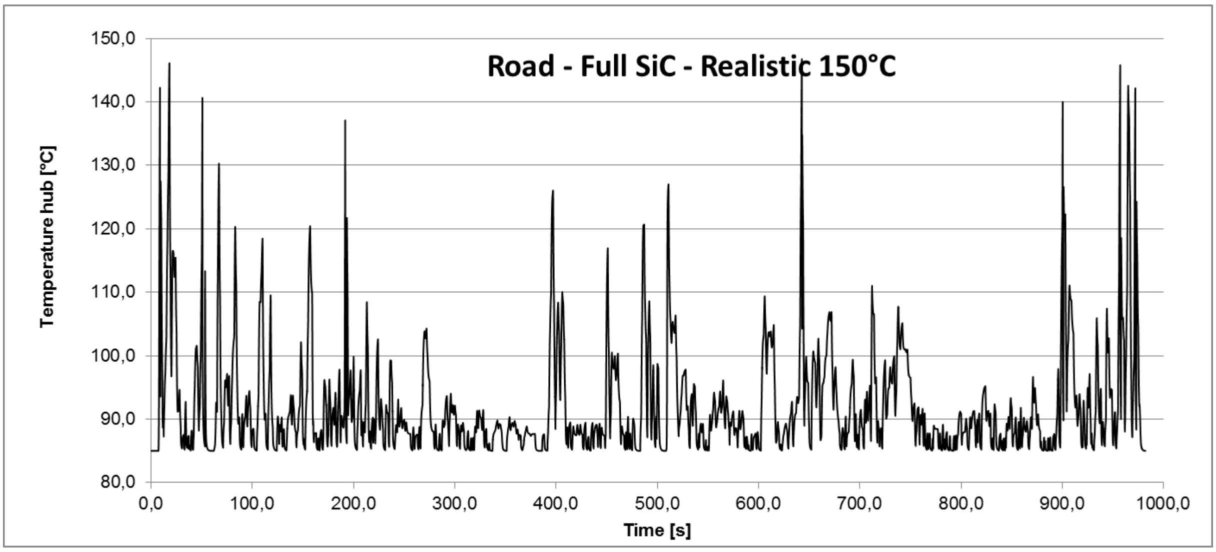

Figure 37: Temperature profile "Full SiC - Realistic 150°C" for Artemis Road

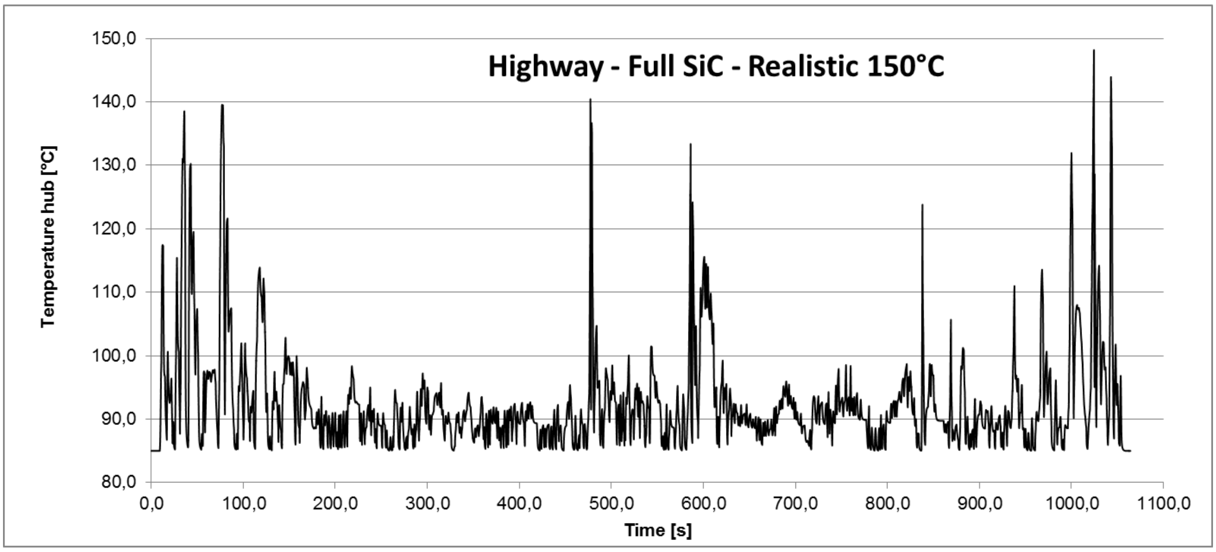

Figure 38: Temperature profile "Full SiC - Realistic 150°C" for Artemis Highway

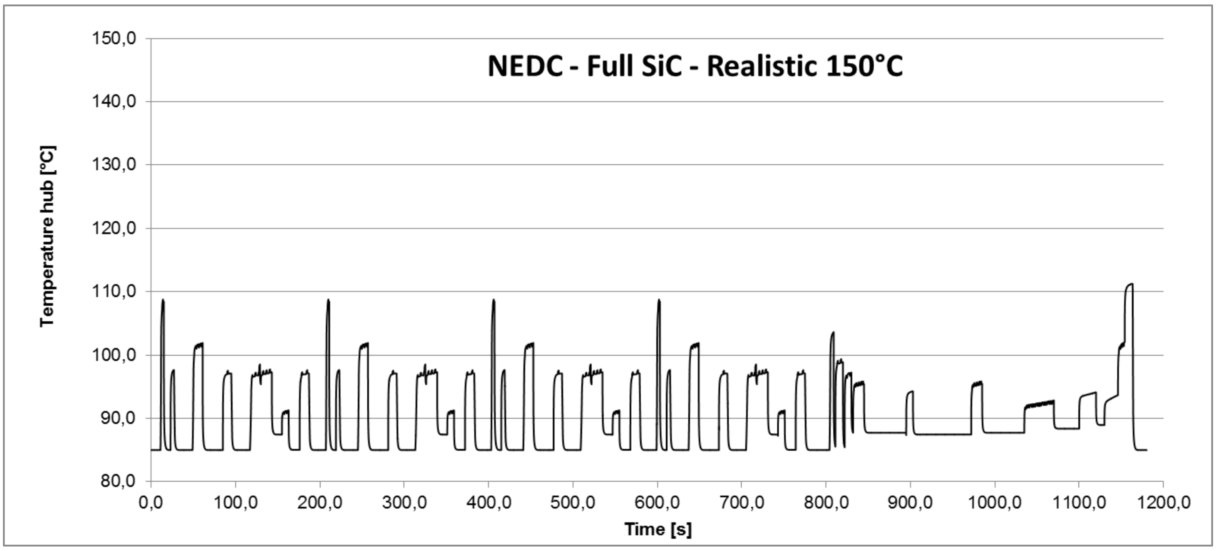

Figure 39: Temperature profile "Full SiC - Realistic 150°C" for NEDC

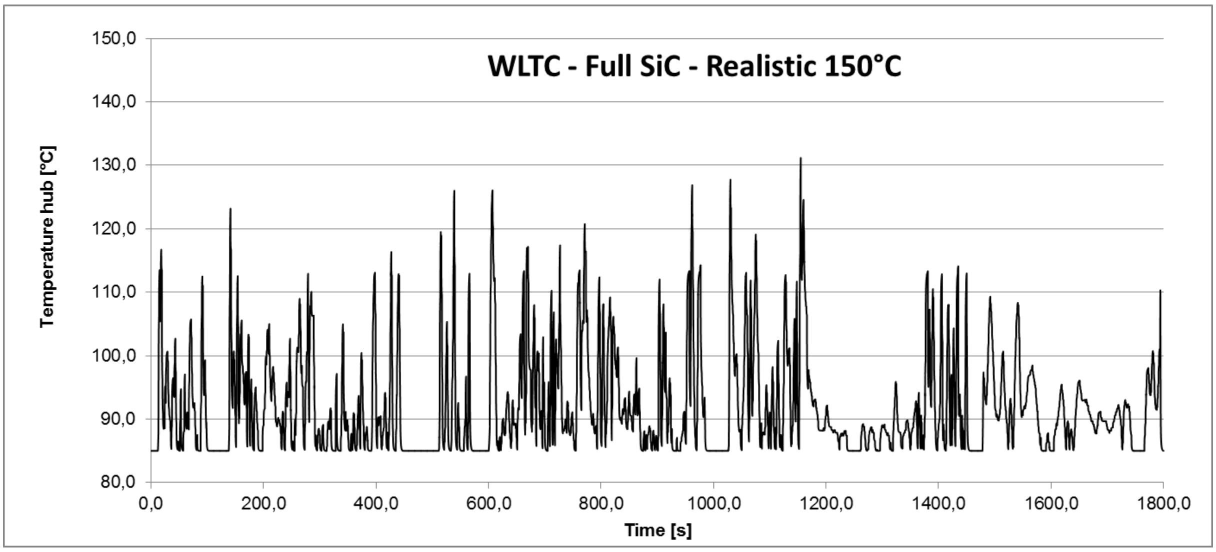

Figure 40: Temperature profile "Full SiC - Realistic 150°C" for WLTC

7.4 Temperature profiles 120 kW drive for HybridPACK Drive

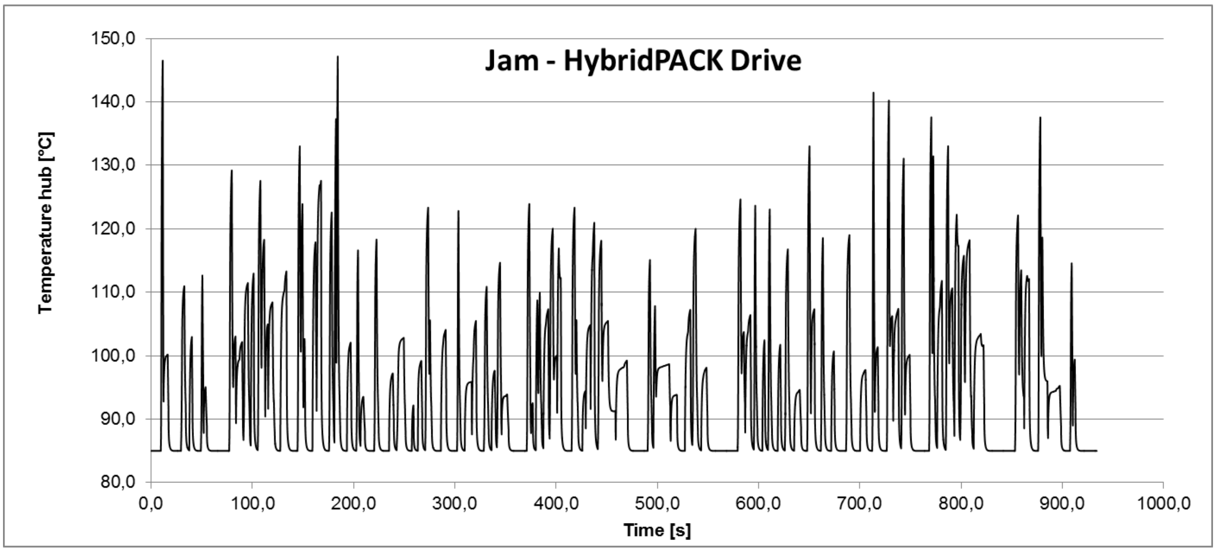

Figure 41: Temperature profile "HybridPACK Drive" for Artemis Jam

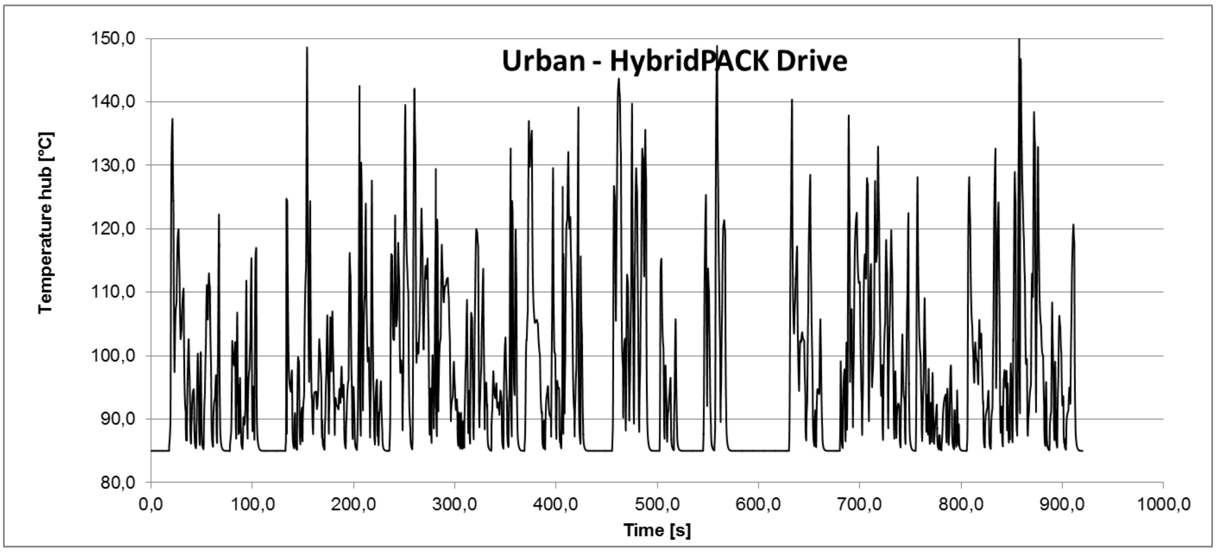

Figure 42: Temperature profile "HybridPACK Drive" for Artemis Urban

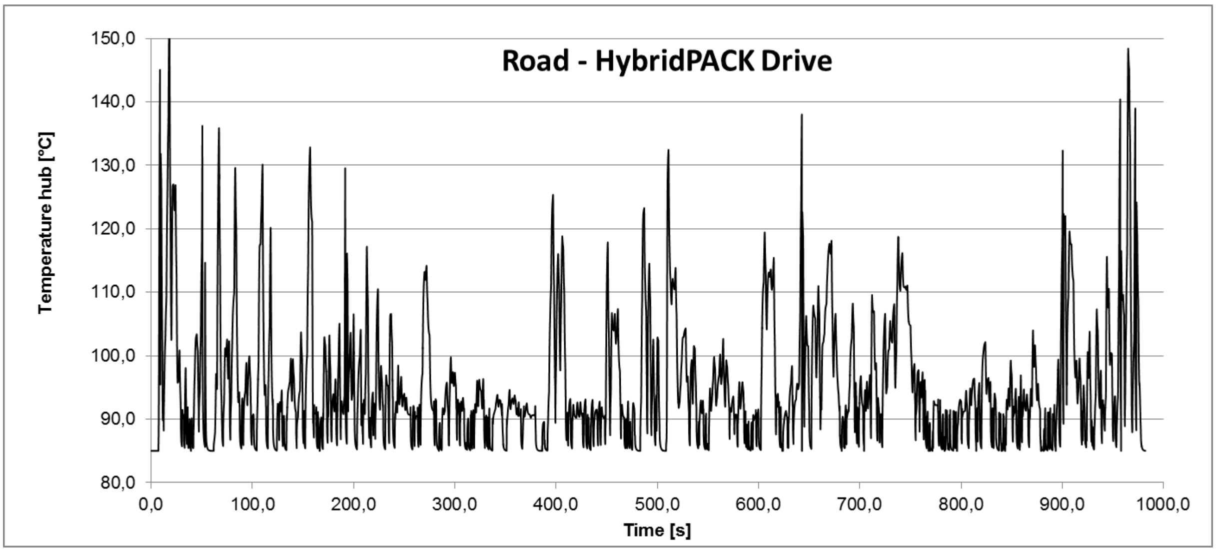

Figure 43: Temperature profile "HybridPACK Drive" for Artemis Road

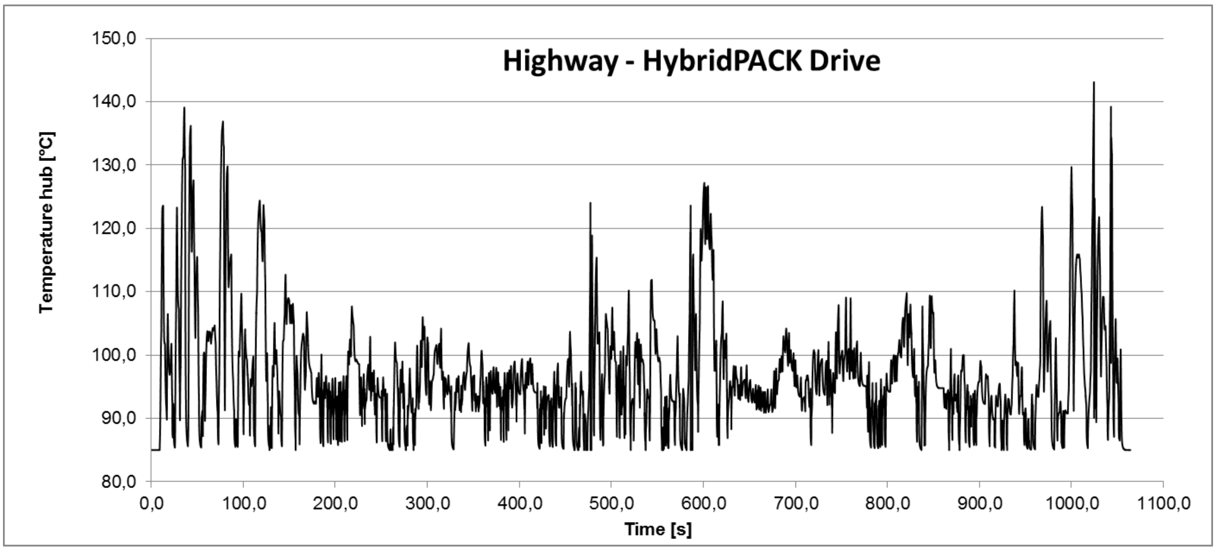

Figure 44: Temperature profile "HybridPACK Drive" for Artemis Highway

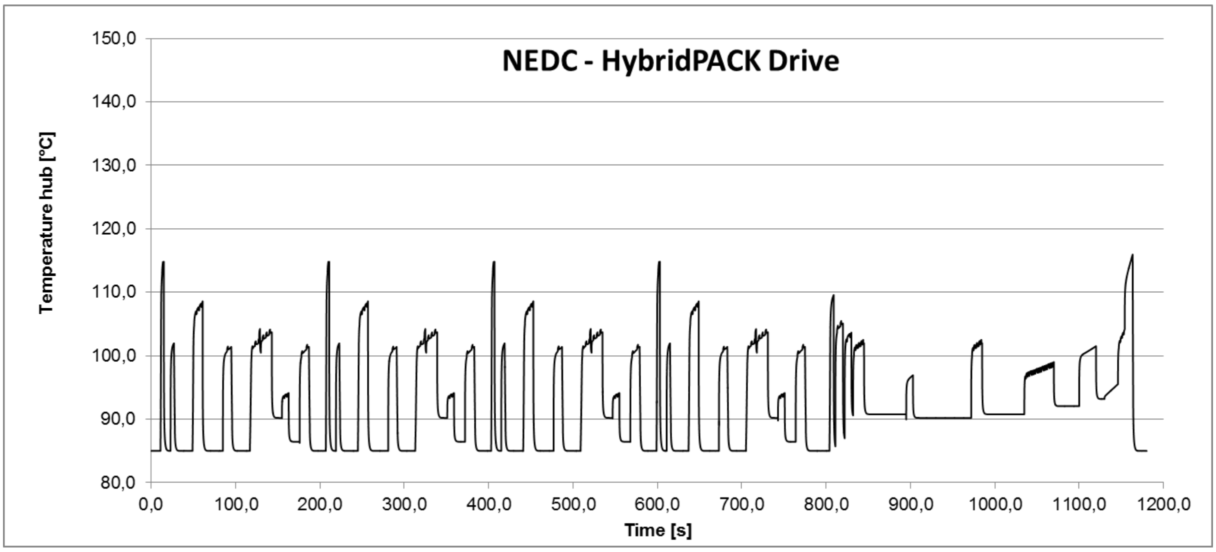

Figure 45: Temperature profile "HybridPACK Drive" for NEDC

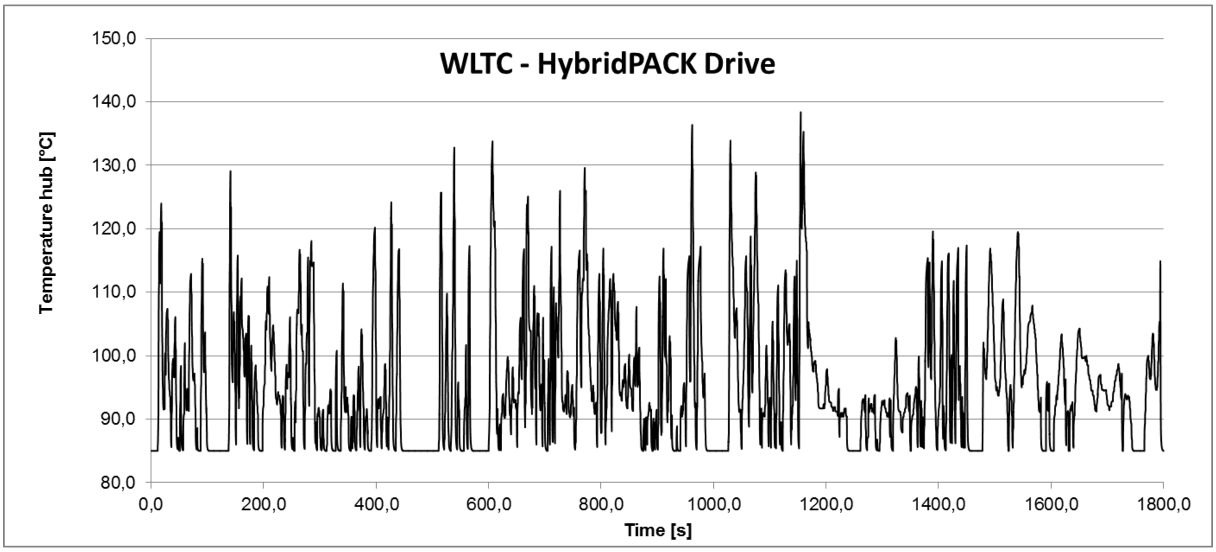

Figure 46: Temperature profile "HybridPACK Drive" for WLTC