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Module Design Methodology for the Conceptualization of a Portable Unit for Providing Heat, Cold and Electricity in BEVs and Buildings

Haider Iqbal Hanif
Doctoral Student
University of Applied Sciences and Arts Hannover
Germany

Dennis Saul
Doctoral Student and Research Assistant
University of Applied Sciences and Arts Hannover
Germany

Henrik Rüscher
Doctoral Student and Research Assistant
University of Applied Sciences and Arts Hannover
Germany

Christian Bohn
Professor
University of Technology, Clausthal
Germany

Lars-Oliver Gusig
Professor
University of Applied Sciences and Arts Hannover
Germany

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Athens Institute for Education and Research
8 Valaoritou Street, Kolonaki, 10671 Athens, Greece
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Abstract

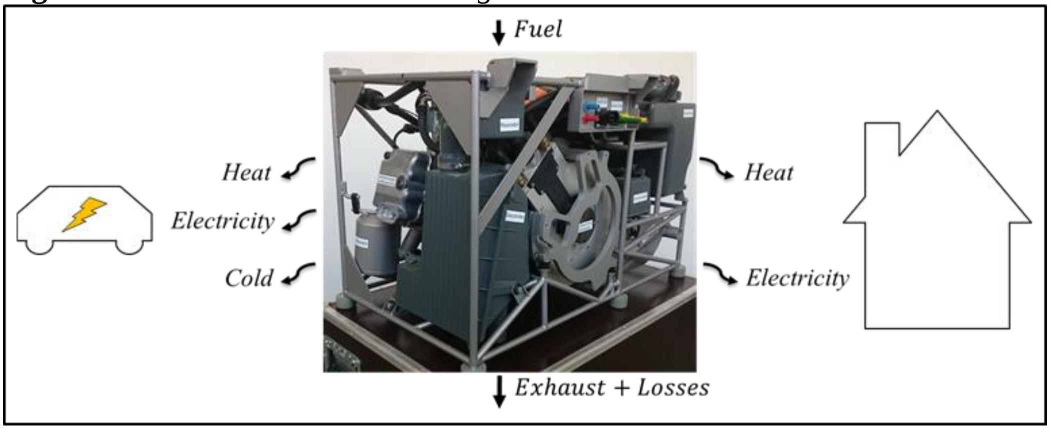
Based upon the current problem of the limited range of battery electric vehicles (BEVs), the thermal conditioning of the battery pack and the passenger compartment, need special consideration. In the ongoing research project "Scalability of mobile micro-combined heat and power (µCHP) units", concepts for µCHP units with an electrical power in range of 1 to 15 kW_{el} are being investigated. From this, a portable prototype will be developed. A µCHP unit combines the generation of electricity and heat. For example as stationary CHP unit for domestic hot water and space heating in residential buildings. A special µCHP unit concept provided by the company IAV GmbH upgrades a normal µCHP unit to a tri-generation of power, heat and cold. This mobile concept, the power conditioning unit (PCU), should be portable to integrate it into the energy and thermal management of BEVs and buildings in order to increase overall efficiency in energy utilization. A previous investigation, carried out by the authors, has shown that the realization of the PCU as portable unit with more than 1 kW_{el} is not possible. This paper explains the application of a new module design methodology (MDM) for the conceptualization of a portable µCHP unit developed by the Institute for Engineering Design, Mechatronics and Electromobility (IKME). Furthermore, according to the MDM, various portable µCHP unit concepts are developed, presented and discussed. Finally, a comparison of portable µCHP units with systems from the state of the technology based on new mathematical indicators is shown. These new indicators reflect the relationship between mathematical quantities like power, weight, installation space and additional BEV range. Due to the MDM, the realization of µCHP unit concepts for the portable application in BEVs and buildings is possible. These concepts could be a solution to reduce CO_2-emissions and increase the range and user acceptance of BEVs.

Keywords: Mobile combined heat and power, Modularization and portable application, Power conditioning unit, Range extender.

Introduction – PCU Concept

The growing demand for energy, such as electricity, heat and cold, requires new applications. In order to meet these demands, µCHP units are being tested at the IKME at the Hanover University of Applied Sciences and Arts with a power in range of 1 to 15 kW_{el}.

Figure 1. *Mobile Power Conditioning Unit*



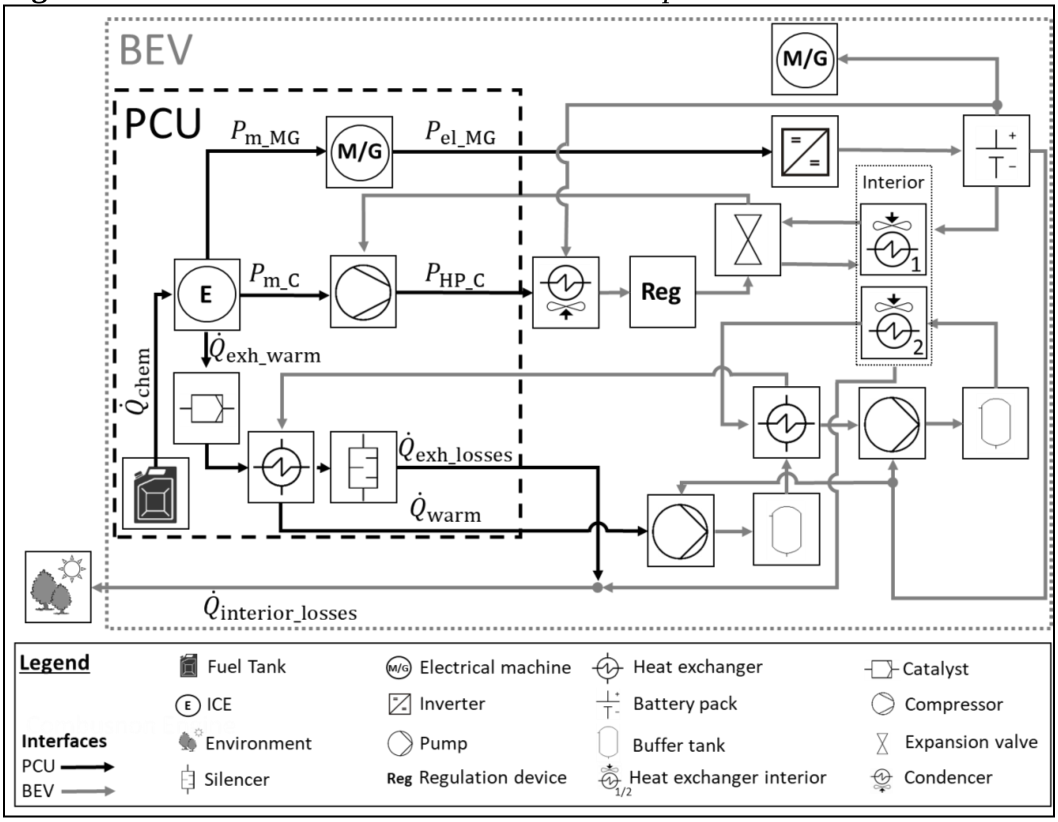
Source: Blank, 2010; Bas, 2011; Hanif et al., 2016.

In these investigations a concept by the company IAV (Gifhorn, Germany), the PCU, is also included. The PCU (Blank, 2010) should be applicable in mobile (vehicles) and in stationary (buildings) areas. Furthermore, the PCU should enable the generation of heat, cold and electricity (see Figure 1). According to Knissel (1999), the cooling demand in buildings (at least in Germany) is not significant. Therefore, the energy supply for cooling in buildings is not considered in this study. In this way, the unit acts as a CHP unit in a building and as a PCU in a BEV. Therefore, the focus lies on integrating the PCU into the BEV (see Figure 2).

The internal combustion engine (ICE) produces mechanical energy by the combustion of fuel (e.g. gasoline in the fuel tank). During this process, exhaust gases are produced, which contain most of the heat. With an exhaust-gas-heat-exchanger, the heat can be decoupled from the exhaust gas and fed to the heater. The heater can be installed in a BEV and in a building if it is not already available. In order to generate electricity, the ICE supplies the generator with mechanical energy.

The ICE drives mechanically the cooling compressor. The refrigerant is compressed by the cooling compressor. The refrigerant absorbs the heat (e.g. from the passenger cabin) at low pressure and temperature and dissipates the heat (e.g. in the environment) at a higher pressure (HP) and temperature.

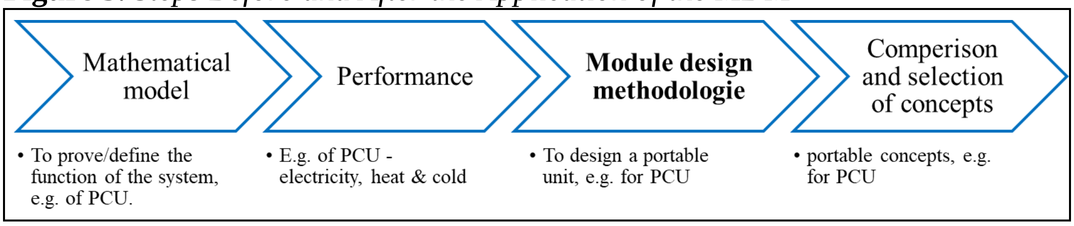
Figure 2. *Power Transmissions between PCU Components and BEV Circuits*



Mathematical Model and Performance of the PCU

The application of the MDM presupposes two steps (see Figure 3). First, the mathematical model should prove the function of the investigated system, e.g. the PCU. A summary of the main mathematical formulas regarding function of several PCU components is provided below. In BEV, the PCU interacts with other systems, which include the power, cooling and heating cycles (see Figure 2).

Figure 3. *Steps Before and After the Application of the MDM*



Furthermore, reference is made to systems from the state of the technology (SOT), e.g. range extenders (RE), CHP units and power generators, in order to clarify the functionalities of the PCU (Hanif et al., 2016). References to the SOT are possible because the PCU combines the functions of these systems in it.

PCU Operation 1 - Electrical Power Supply (RE Operation)

All mentioned SOT systems need fuel, which the fuel tank stores. The fuel consumption $\dot{m}_{\mathrm{F}}$ of the ICE and calorific value H_{C} of the fuel describe the necessary chemical energy $\dot{Q}_{\mathrm{chem}}$.

$$\dot{Q}_{\mathrm{chem}} = \dot{m}_{\mathrm{F}} * H_{\mathrm{C}} \qquad (1)$$

As a result of fuel combustion, the ICE generates mechanical power P_{mech}. The value x is a part of the mechanical power that is transmitted to the generator. x can assume a value between 0 and 1. In this case, x is equal to 1. The electrical power $P_{\mathrm{el\_MG}}$ is calculated with η_{G}, the efficiency of the generator.

$$P_{\mathrm{el\_MG}} = \eta_{\mathrm{G}} * P_{\mathrm{mech}} * x \qquad (2)$$

During this operation, heat is released to the environment without any benefit because there (e.g. in summer) are no heat demands.

PCU Operation 2 - Electrical and Heat Power Supply (CHP Unit Operation)

In order to receive heat power $\dot{Q}_{\mathrm{f1}}$ the combustion of fuel in the ICE is required. The exhaust gas $\dot{m}_{\mathrm{f1}}$ (Fluid 1 with the index $_{\mathrm{f1}}$) flows in the exhaust-gas-liquid-heat-exchanger. Additional heat transfer media $\dot{m}_{\mathrm{f2}}$ (Fluid 2 with the index $_{\mathrm{f2}}$) in the exhaust-gas-liquid-heat-exchanger can decouple the heat $\dot{Q}_{\mathrm{f2}}$ from the exhaust gas. Heat transfer media can be water or oils (liquids).

$$\dot{Q}_{\mathrm{f1}} = \dot{m}_{\mathrm{f1}} * c_{\mathrm{p,f1}} * (T_{\mathrm{f1,in}} - T_{\mathrm{f1,out}}) \qquad (3)$$

$$\dot{Q}_{\mathrm{f2}} = \dot{m}_{\mathrm{f2}} * c_{\mathrm{p,f2}} * (T_{\mathrm{f2,in}} - T_{\mathrm{f2,out}}) \qquad (4)$$

The heat power $\dot{Q}_{\mathrm{warm}}$ of a liquid-air-heat-exchanger (heater) depends on the medium that absorbs heat power $\dot{Q}_{\mathrm{f2}}$ from the medium that gives off heat power $\dot{Q}_{\mathrm{f1}}$ in the exhaust-gas-liquid-heat-exchanger. The heater heats the incoming air at the outside of the heater wall $\mathrm{A}_{\mathrm{wall}}$ (surface of the heater wall) to the temperature T_{air} (warm air) due to the liquid flow with $T_{\mathrm{f2,out}}$ at the inside of a heater wall $\mathrm{A}_{\mathrm{wall}}$. The warm air with $\dot{Q}_{\mathrm{warm}}$ flows to the interior of a BEV to increase occupant comfort (Böckh and Wetzel, 2017; Minnrich et al., 2017).

$$\dot{Q}_{\mathrm{warm}} = \mathrm{A}_{\mathrm{wall}} * k * (T_{\mathrm{f2,out}} - T_{\mathrm{air}}) \qquad (5)$$

According to Böckh and Wetzel (2017) the reciprocal of the heat transfer coefficient k of a flat wall is the sum of the reciprocal values of the heat transfer coefficients α (of the fluid 2, heater wall and air).

$$\frac{1}{k} = \frac{1}{\alpha_{f2}} + \frac{1}{\alpha_{heater\,wall}} + \frac{1}{\alpha_{air}} \qquad (6)$$

PCU Operation 3 - Electrical, Heat and Cold Power Supply (PCU)

During this operation mode, the PCU supplies electricity, heat and cold for use in the BEV. A mechanical interface divides the mechanical power P_{mech} from the ICE to the generator and to the compressor. This mechanical interface can be a belt or a gear. Via a compressor, the refrigerant is compressed with power $P_{\mathrm{HP\_C}}$. The compressor efficiency is symbolized by η_{C}.

$$P_{\mathrm{HP\_C}} = \eta_{\mathrm{C}} * P_{\mathrm{mech}} * (1 - x) \qquad (7)$$

During the PCU operation 1 (RE), only the generator uses mechanical power P_{mech} (see equation 2). During the PCU operation 3 the compressor consumes the (1-x)-part of the mechanical power P_{mech} too (see equation 7). With *x* equal to 1, the PCU supplies heat $\dot{Q}_{\mathrm{warm}}$ and electrical power $P_{\mathrm{el\_MG}}$ (PCU operation 2). With *x* equal to 0, the PCU supplies heat $\dot{Q}_{\mathrm{warm}}$ and cold $P_{\mathrm{HP\_C}}$. With *x* between 0 and 1, the PCU supplies all three forms of energies. In equation 2 and 7, the losses due to the waste heat are neglected in order to simplify. Some authors (Flieger, 2014; Großmann, 2013) describe the air conditioning of the vehicle, based on measurements of numerical functions, that can be used for the given energy generating systems (Minnrich et al., 2017).

The developer has to choose a performance in advance (see Figure 3). The performance can be the whole power output of the system, e.g. the sum of heat, cold and electrical power as output of the PCU. After the aforementioned steps, several concepts of the portable unit (PU) can be developed with the MDM (see Figure 4). After the MDM, these concepts can be compared (see Figure 3) to select the requirements-based concepts.

Module Design Methodology for the Conceptualization of a PU

This methodology is specially developed for mechatronic systems, in which several components work together. Generally, the hardware (a machine) is used in one area, e.g. a RE in a BEV or a CHP unit in a building. The PCU can be used in BEVs and buildings. To realize the application of the PCU in both areas, it must be easy to assemble and disassemble. For easy installation, the PCU needs to weigh as little as possible, e.g. less than 40 kg to be portable by users (driver or householder) according to DIN 33411 5 (1999).

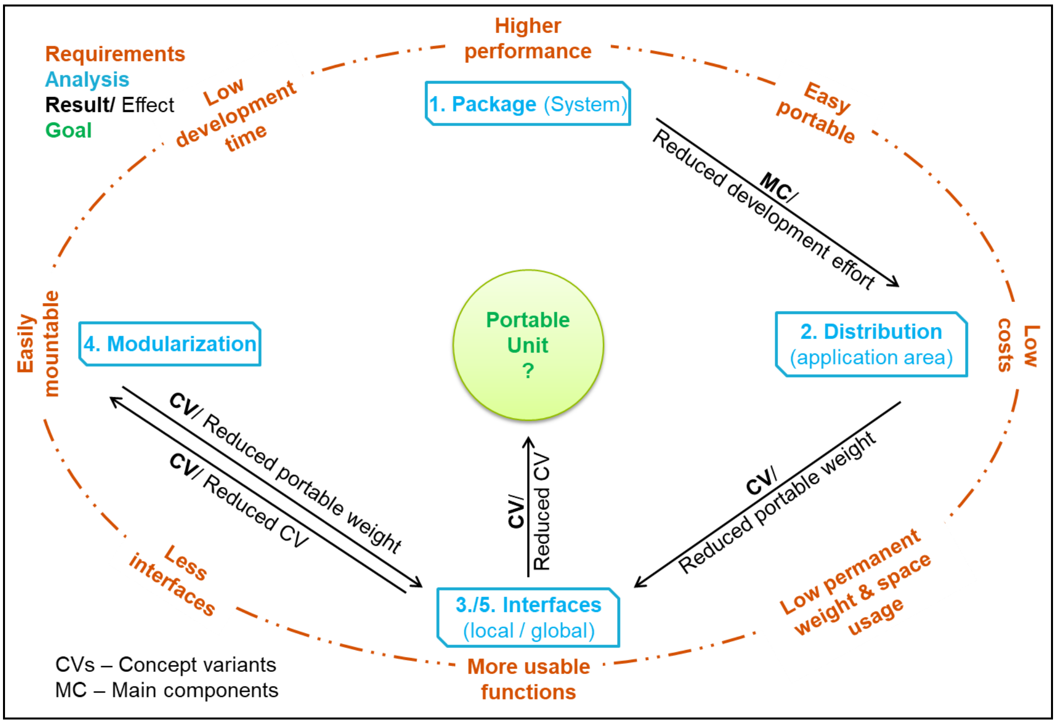
Hanif et al. (2016) has shown that the PCU with a power up to 1 kWel is not portable as single unit due to the high weight of its components. In any case, the demand in BEVs and buildings is higher than 1 kWel (Beetz et al., 2010; Minnrich et al., 2014).

There are several possibilities to reduce the machinery weight. First, using lightweight metal (Friedrich, 2013), e.g. aluminium instead of steel. Second, using lightweight technology (Hofmann, 2014), e.g. gasoline ICE instead of diesel ICE. Third, improving construction (Eckstein et al., 2011), e.g. using Finite-Element-Method-analysis. Finally, producing the components with better manufacturing processes (Kranz, 2017; Brendecke et al., 2008), e.g. casting instead of milling.

The selection of lightweight materials is limited by a few parameters, e.g. maximum permissible load (temperature, forces, pressure etc.), further costs and development time. Many components are externally sourced (e.g. ICE and generator of the PCU), or already existed components (e.g. the compressor in the BEV) are used because own development is too time-consuming and associated with more costs. Therefore, the weight-reduction changes to such components are not effectively possible.

Previously mentioned or already known possibilities of weight reduction (e.g. using the lighter-weight technology) are not yet sufficient, because requirements regarding weight are even more critical. The PCU must be portable and applicable in two areas (buildings and vehicles). This paper shows a methodology (MDM, see Figure 4) that reduces the weight of such a unit in a completely new way to develop a unit for portable use.

Figure 4. *MDM for the Conceptualization of a Portable Unit*



The MDM considers various requirements (e.g. easy portable, low development time and more useable functions) and comprises four analyses, which provide various results to answer the issue of unit portability. With the MDM, the steps follow from the outside to the inside, focusing on the development goal of a PU. In addition to these requirements, the developer can also define further or others. Each individual analysis is a cause for different effects on the result and ultimately on the goal. Among the four analyses, the given package (e.g. the PCU) is the first analyzed.

In the first analysis (package), to reduce the development effort, the main components (MC) of the package are to define depending on maximal weight, e.g. the ICE, the generator, the compressor and the fuel tank. In analysis, the distribution, some of the MC can be permanently distributed in application areas to reduce the weight of the PU. In analysis, the modularization, the PU package can be defined as several PU modules consisting of MC to reduce the portable weight of each portable module as well. The result or output of the distribution and modularization analysis is several concept variants. After the distribution and the modularization of the MC, the interfaces of each concept variant (CV) should be analyzed individually. In general, the result is the same, if the order of the two analyses (distribution and modularization) is interchanged, but the development effort will be different. After the analysis of interfaces, there are only several CVs left, which should not have any doubt regarding function.

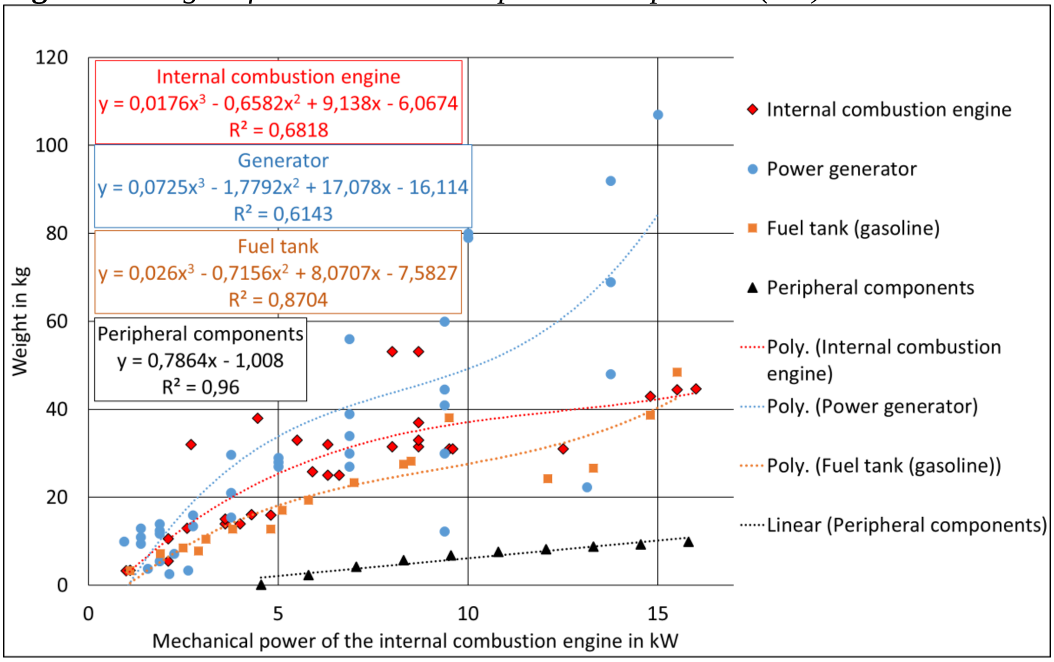
These CVs are the goal (PU), which have to be compared to select the preferred concepts as a PU (see Figure 3 and 6 to 8). Subsequently, the four analyses of the MDM are explained more precisely as well as their results to achieve the goal (PU).

Analysis of a Given Package (PCU) to Set the MC and to Reduce Development Effort

In order to estimate the package regarding the weight, only the MC that are heavy relative to other components in the system (e.g. PCU) are considered. The expression “main” by the MC refers to the weight and not to the function of the components. The function analysis of the system must be done before MDM, which is already shown due to the mathematical model (see Figure 3).

A balance must be achieved between the accuracy of results and the development time effort in choosing the MC. The more MC, the higher the development time expenditure, but the more accurate the solution will be. The developer has to set this compromise according to the available development time, the quantity and the weight of components. During this analysis four PCU components, the ICE, the generator, the compressor and the fuel tank, are considered as MC. These components are chosen because of their high weight and installation space relative to other components (e.g. the heat exchanger and silencer) in the PCU.

Figure 5. *Weight of the Main and Peripheral Components (PU)*



Source: (ICE and generator manufacturer, 2017).

Figure 5 shows the weight of the MC and peripheral components of the PU, which depends on mechanical power of the ICE. In this way, the relationship between the PCU performance and the weight of the PU based on the regression weight functions (see Figure 5). The regression functions (linear and polynomial) can be changed depending on which and how many components (with its performance) are considered, which in turn affects the coefficient of determination R^2 (see Figure 5). The fuel tank regression weight function takes into account the fuel content (gasoline) for eight hours of PCU operation. The peripheral components included in the PU are the clutch and the mechanical connection between the ICE, the generator and the compressor. Peripheral components are estimated at 10 % of the total weight of the respective ICE. The assumption with 10 % is based on the PCU prototype with 2 kW_{el}. For this reason, the regression function of peripheral components is a straight line. Analog to Figure 5 and the approximation of the volume can be calculated of each component (Hanif et al., 2016).

After the package is analyzed, the way to the analysis of distribution or to the analysis of modularization can be taken (see Figure 4). Due to interface of the compressor only to the BEV, the distribution as the second analysis is the better way regarding the development effort. In following, the way to the analysis of distribution (see Figure 4) is preferred.

Analysis of the Distribution of the MC in Application Areas to Reduce the Portable Weight of the PU

This analysis depends on the application areas and the system, which should be portable. The PCU can be used in two areas, in BEVs or in buildings. In this analysis all CVs, which are created by the distribution of the MC in application areas, have to be considered. All other components of the system except of the MC are supposed to be peripheral components. Some of them belong to the PU (e.g. the catalyst) and others (e.g. the heat exchanger and silencer) are fix installed in the application areas. The fix installed peripheral components are not considered in the MDM (regarding weight), but in the design process after the MDM.

Docking processes of the PU cause fluid losses through the heat exchanger interfaces (in the BEV and the building) and compressor interfaces (in the BEV). This requires additional security measures, complex interfaces and higher assembly, disassembly and application effort for the user. For this reason, the PCU components of the heating cycle are fix installed in both areas and of the cooling cycle are fix installed in a BEV only. The compressor must be permanently installed in the vehicle because of the permanent sealed interface between the compressor and the cooling cycle in the BEV too. Therefore, the compressor does not count towards the PU. The fix distribution of the heating and cooling cycle is useful due to the fact that the PU has fewer interfaces and lead to low portable weight of the PU as well. Thus, the non-distributed MC belong to the PU (see Table 1). The MC, which are distributed, are permanently installed in the application areas. The distributed MC do not belong to the PU and are not listed in the Table 1.

For a given number *Q* (a natural number) of the MC, a total number of 2^Q CVs can be obtained by this analysis. Including the CV (CV-No. 16, see Table 1) that all MC are permanently installed in the application areas.

Table 1. *CVs by the Distribution of the MC in a BEV and a Building*

<table>
<tr><td rowspan="9">Q (MC quantity) = 4
$Q > 0 \land Q \in \mathbb{N}$

CVs (total) = $2^Q = 2^4 = 16$
MC:
1 – Fuel tank
2 – ICE
3 – Generator
4 – Compressor</td><th>CV-No.</th><th>MC of PU</th><th>CV-No.</th><th>MC of PU</th></tr>
<tr><td>1</td><td>1</td><td>9</td><td>2</td></tr>
<tr><td>2</td><td>1, 2</td><td>10</td><td>2, 3</td></tr>
<tr><td>3</td><td>1, 2, 3</td><td>11</td><td>2, 3, 4</td></tr>
<tr><td>4</td><td>1, 2, 3, 4</td><td>12</td><td>2, 4</td></tr>
<tr><td>5</td><td>1, 2, 4</td><td>13</td><td>3</td></tr>
<tr><td>6</td><td>1, 3</td><td>14</td><td>3, 4</td></tr>
<tr><td>7</td><td>1, 3, 4</td><td>15</td><td>4</td></tr>
<tr><td>8</td><td>1, 4</td><td>16</td><td>-</td></tr>
</table>

In application areas more components are distributed, the lower the portable weight will be, but the cost of components increase. The permanent place and weight usage due to components in the application areas will increase as well. Therefore, the developer has to compromise between portable weight on the one side, the cost, permanent place and weight usage of components in application areas on the other side.

Analysis of Local and Global Interfaces after Distribution of MC to Reduce the CVs

In MDM, the interfaces are subdivided in local and global. The interfaces between the components or modules of the system (e.g. PCU) are local. The interfaces between the system (e.g. PCU) and the application areas (e.g. BEV and building) are global. In this analysis, both interfaces have to be considered. Previous analysis has given several CVs (16) as output (see table 1). Because of integration of the PCU in application areas, the permanent place and weight usage in BEV is very critical, which is not always the case in buildings.

The air conditioning or cooling in buildings (West Germany) is of little importance. The reason is the lower energy consumption for lighting and equipment (printer, PC, etc.), better air circulation and exchange in the rooms and better protection against sunlight. As a result, the investment, operating and maintenance costs for building services are falling. The saved costs can compensate for additional costs (e.g. for distributed components). (Knissel, 1999)

Considering the requirement that the PCU should supply only the BEV with cold air, in several CVs the compressor can be removed if used in the building. For example, in a PU with the ICE and the generator (CV-No. 10, see table 1), the compressor and the fuel tank are fix installed in both application areas. In this CV, the compressor can be removed from the building because it is only needed in BEV. Not all CVs due to previous analysis are useful because of the inadmissible function of local and global interfaces.

In both analyses (the distribution and the modularization), the output (several CVs) is proportional to the number of the MC. It is more sensible to eliminate unnecessary CVs, or to adjust the CVs before proceeding with the next analysis. Some CVs for the PU are not necessary, because the compressor must be permanently installed in BEV (global interface). The numbers of those CVs are underlined (see table 1). The analysis of distribution as second way is the most sensible way, because the development time will be less due to exclude several CVs. The CV-No. 16 without any component in the PU is also excluded because of its high costs due to several occurrences of the components. To choose or to adjust the CVs, the developer has to consider the requirements in advance to save the development time during next analysis, the modularization.

Analysis of the Modularization to Reduce the Portable Weight of Each PU

Only the CVs, which are chosen (not underlined, see Table 1), will be analyzed regarding the modularization by this step. By the modularization only the MC of the PU are important and the distributed or permanent installed components (MC and peripheral) in the application areas are not significant. The quantity of the modules in the PU depends on the quantity of the MC in corresponding CVs (see Table 1). The non-excluded CVs consist with a maximum of three MC (see Table 1).

Due to the modularization, further concepts (see Table 2) for the respective CVs from the previous analysis (see Table 1), are created. The number of concepts in this analysis is defined by the mathematical term "$2^J - J$" for each CVs (see Table 1). J is the quantity of MC per CV of PU from previous analysis (interfaces, see Table 1).

The term "2^J - J" in this analysis is applicable for up to three MC per CV. J is a natural number.

Table 2. *Concepts Quantity by Modularization of Components per CV of PU*

<table>
<tr><th>J : MC per CV
$0 < J < 4 \land J \in \mathbb{N}$</th><th>CV-No. (see table 1)</th><th>MC of PU</th><th>J</th><th>2^J- J</th><th>Concepts Quantity ∑</th></tr>
<tr><td rowspan="7">Concept/CV = 2^J- J

MC:
1 – Fuel tank
2 – ICE
3 – Generator</td><td>1</td><td>1</td><td>1</td><td>1</td><td rowspan="7">14</td></tr>
<tr><td>2</td><td>1, 2</td><td>2</td><td>2</td></tr>
<tr><td>3</td><td>1, 2, 3</td><td>3</td><td>5</td></tr>
<tr><td>6</td><td>1, 3</td><td>2</td><td>2</td></tr>
<tr><td>9</td><td>2</td><td>1</td><td>1</td></tr>
<tr><td>10</td><td>2, 3</td><td>2</td><td>2</td></tr>
<tr><td>13</td><td>3</td><td>1</td><td>1</td></tr>
</table>

The concepts of three CVs (CV-No. 1, 2 and 3, see Table 2) with one, two and three MC are shown as example in Table 3. Due to the modularization of the PU package in several modules, the portable weight reduced as well. A PU module can consist of one or more MC. The less the MC in a PU module, the less the portable weight will be or conversely.

A PU module with more than one main component must be equipped with the appropriate interface. The plus symbol between the main component numbers of a module describes the existing of a local interface and the comma symbol between the main component numbers describes, that the user has to assemble these MC (of a PU module) manually with the appropriate interface (see Table 3).

The relationship between the number of modules in a PU and the assemble effort of the PU in the application areas is proportional. For example, concept 4 (see Table 3) consists of three modules as individually main component, which must be assembled by the user one by one in the application area. Concept 6 includes only one module with existing interfaces between the three MC. The user needs less assemble effort with concept 6 relative to concept 4.

Table 3. *Modules in Several Concepts of PU*

<table>
<tr><td rowspan="9">J : MC per CV
$0 < J < 4 \land J \in \mathbb{N}$

Concept/CV = 2^J- J

MC:
1 – Fuel tank
2 – ICE
3 – Generator</td><th>CV-No. (see table 2)</th><th>Concept</th><th>Modules of PU</th><th>Module quantity of PU</th></tr>
<tr><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>2</td><td>2</td><td>1, 2</td><td>2</td></tr>
<tr><td>2</td><td>3</td><td>1 + 2</td><td>1</td></tr>
<tr><td>3</td><td>4</td><td>1, 2, 3</td><td>3</td></tr>
<tr><td>3</td><td>5</td><td>1+ 2, 3</td><td>2</td></tr>
<tr><td>3</td><td>6</td><td>1 + 2 + 3</td><td>3</td></tr>
<tr><td>3</td><td>7</td><td>1, 2 + 3</td><td>2</td></tr>
<tr><td>3</td><td>8</td><td>1 + 3, 2</td><td>2</td></tr>
</table>

Analysis of Local Interfaces after the Modularization of MC (in PU) to Reduce the CVs

According to the MDM, after the analysis, the modularization, the interfaces have to be analyzed too (see Figure 4). After the modularization, the local interfaces have a higher priority than the global interfaces. Concept 8 is underlined (see Table 3) because the local interface between the fuel tank and the generator is inadmissible. Therefore, this concept can be eliminated. Due to the interface analysis of all concepts (see Table 2), many of them have to be eliminated.

The eleven retained concepts are listed in Table 4, which have functional correct (admissible) local and global interfaces. In the column "Portable unit" the modules are shown, which are defined according to modularization analysis of MC. A module with more than one main component is highlighted by green color. The permanent installed MC in each concept are defined as one module in buildings and BEVs as described by the analysis, the distribution of MC. The quantity of interfaces is necessary to prefer or to eliminate the concepts during the concept rating and selection.

After the application of the MDM, the CVs (see Table 4) are compared with each other to select one or more demand-appropriate concepts (see Figure 3). For the comparison of the eleven concepts (see Table 4) several criteria are considered, like less portable weight, less installation space, easy interfaces/integration, high output useable energy and fewer costs of the PCU.

Table 4. *Functional Concepts of the PU to Applicate in BEVs and Buildings*

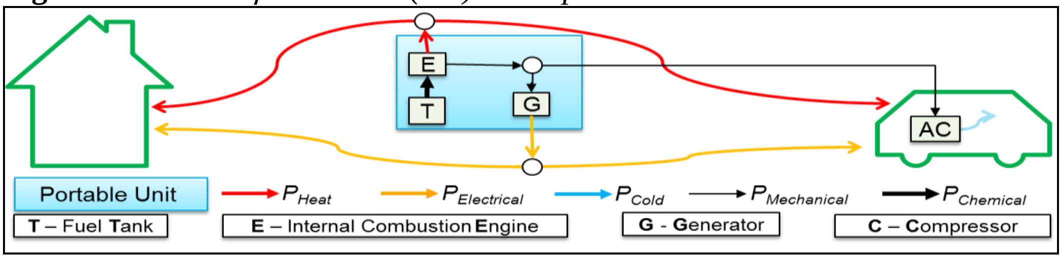
Concept	**Power conditioning unit (PCU)**								
	Portable unit				**Permanent installed MC in**		**Local interfaces**		
	T	**E**	**G**	**C**			**Maximum interfaces of MC in**	**Maximum PU interfaces to the MC in**	
	Fuel Tank	ICE	Generator	Compressor	**Building**	**BEV**	**PU**	**Building**	**BEV**
1	x				E, G	E, G, C	0	1	1
2	x	x			G	G, C	1	1	2
3	x	x			G	G, C	0	1	2
4	x	x	x			C	2	0	1
5	x	x	x			C	0	0	1
6	x	x	x			C	1	0	1
7	x	x	x			C	1	0	1
8		x			T, G	T, G, C	0	2	3
9		x	x		T	T, C	1	1	2
10		x	x		T	T, C	0	1	2
11			x		T, E	T, E, C	0	1	1

After the comparison, according to Richtlinie VDI 2222 (1997), the three PU concepts (see concepts 5, 4 and 7 in Table 4 and in Figures 6 to 8) are preferred for the further comparison and selection. In the following, a PU is regarded as a portable µCHP unit, because it can supply heat and electrical power from the ICE and the generator. These concepts are qualitatively described and compared. The housing may be implemented as one or more portable modules to subsequently encapsulate the assembled µCHP unit in a BEV (to a PCU). The housing takes into account the thermal and acoustic insulation too.

Comparison and Selection of the Portable µCHP Unit Concepts

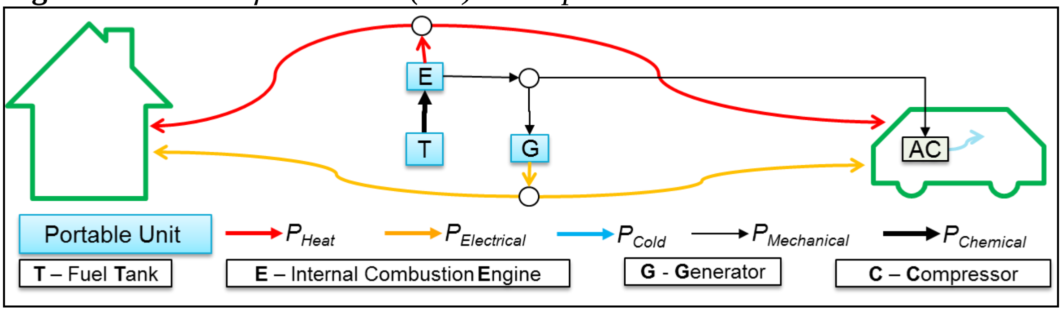
With the concept 5 (see Table 4 and Figure 6), the PU consists of three MC as one module. Therefore, the user saves much time because of less integration effort. For the user, the assembly effort is less because the developer must assemble the MC in the PU itself. Then the user can assemble the PU as only one module in corresponding area. However, the portable weight of this PU restricts the performance. Hence, this concept is suitable for low electrical power range because the PU includes the weight of all MC except the compressor.

Figure 6. *Portable µCHP Unit (PU) Concept 5*



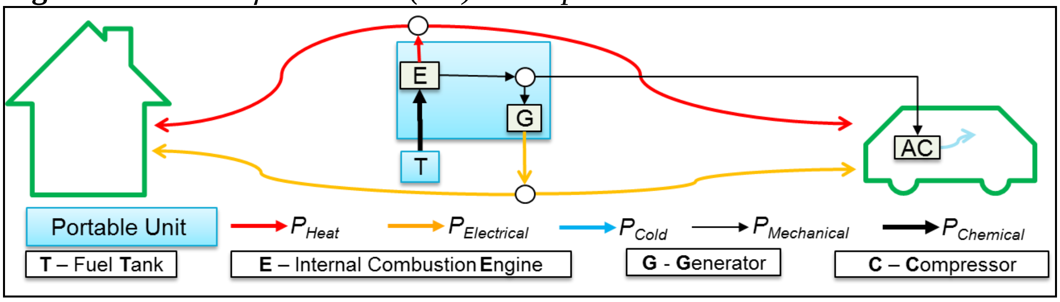
With the concept 4 (see Table 4 and Figure 7), the PU consists of three MC each as an individual module. The modules should be individually portable by the user. The user can integrate them chronologically in the corresponding area. This concept is suitable for higher electrical power range compared to concept 5. The assembly effort for developers is less, because the user assembles the modules of the PU. Furthermore, the costs are higher relative to concept 5, due to new interfaces (fast coupling) between the PU modules. Due to several modules, much more permanent installation space and weight can be effort in corresponding application area relative to concept 5.

Figure 7. *Portable µCHP Unit (PU) Concept 4*



With the concept 7 (see Table 4 and Figure 8), the PU consists of two modules. The PU has fewer modules than the concept 4 but more modules than concept 5. The interface between fuel tank and ICE in the PU is a fuel feed pipe, which is very flexible and should not cause the user any problem during the connection of both modules. The user saves much time relative to the concept 4 due to already existing interface between the ICE and the generator. Furthermore, the concept 7 can offer better performance than the concept 5 but lower than the concept 4 with the same maximum portable weight.

Figure 8. *Portable µCHP Unit (PU) Concept 7*

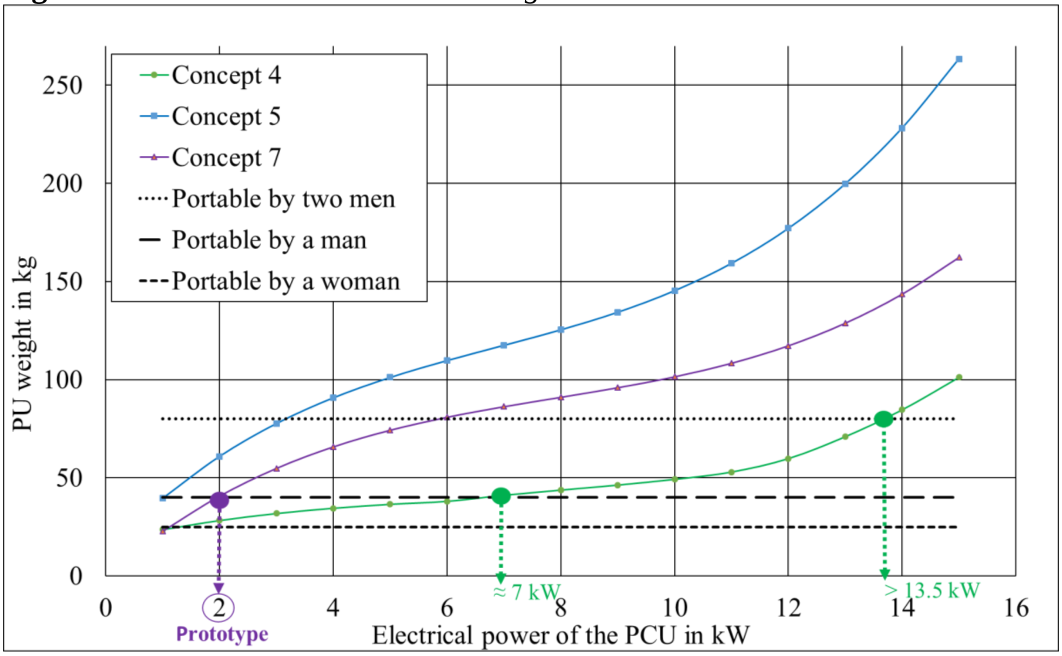


In Figure 9, the result of the MDM regarding maximum weight of the PU modules is presented, which is calculated with the approximated function of the MC, see Figure 5. Several factors influence the choice of PCU performance, e.g. application areas, customer demands and financial feasibility. The curves show the maximum module weight of the three chosen PU concepts (4, 5 and 7) as a function of the PCU electrical power.

Furthermore, the maximum portable load for up to two persons is represented in the Figure 9 too. By grasping of a stacking box (e.g. PU) a woman can carry up to 25 kg and a man can carry up to 40 kg without technical tools, according to DIN 33411, 5 (1999). In this way, two men can carry up to 80 kg. The intersections between the curves of module weight (PU) and portable weights by users/persons set the limit of possible portable concepts with appropriate PCU performance.

The concept 7 allows a woman up to 1 kW_{el} and a man up to 2 kW_{el}. Up to 6 kW_{el} the PU of concept 7 can be carried by two men. The weight difference between concept 5 and 7, increases with higher electrical power. Respectively concept 7 weighs less due to the separate fuel tank compared to concept 5. The concept 4 can be portable up to 2 kW_{el} by a woman, up to 7 kW_{el} by a man and up to 13.5 kW_{el} by two men. Among these three concepts the concept 4 can provide the application areas with higher useable energies by the same portable weight, but the assemble effort is much higher due to several modules of the PU as well, see Figure 7.

Figure 9. *PU Module with Maximal Weight*

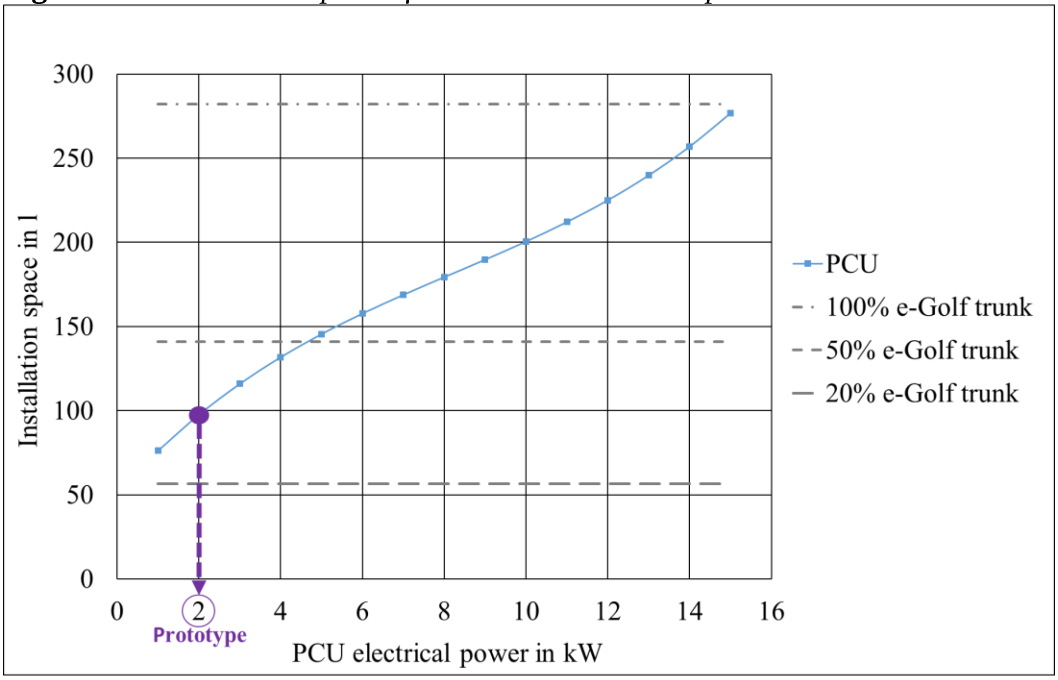


In Figure 10, in addition to the weight, the installation space of the PCU is shown. The installation space in the BEVs is much critical than in buildings. To choose or to set a limit of concepts regarding the installation space, the BEV “Volkswagen e-Golf” is taken as a mobile application area. According to Adamitz et al. (2017) in the BEV Volkswagen e-Golf, the trunk is the suitable integration area for the PCU. In this way, the limit is set by the trunk storage space of the Volkswagen e-Golf. The intersection between the curves of the PCU volume and the trunk storage space of the Volkswagen e-Golf sets the limit of possible portable concepts with appropriate PCU performance (see Figure 10).

Depending on the vehicle or the building, the limit of the possible concepts can be different as shown in figure 10. The trunk storage space for miniature vehicles (BEV/ motor vehicle) is about 250 liters (see Figure 10 and Hanif et al., 2016). Thus, the use of a PCU from 1 to 15 kW_{el} would be almost applicable in every compact class BEVs.

The weight and installation space of a PCU depend on its performance. The weight and volume of systems always exist. The user can carry only a limited weight. All vehicles, not only BEVs, have to provide much more power with a higher weight, whereas, the volume of a system is critical for all application areas including building and vehicle. Due to the use of an additional system, like the PCU in the application areas, the useable space will be much less. The aim is to occupy as small as possible space in BEVs and buildings.

Figure 10. *Installation Space of the PCU without Compressor*



PCU with the Operation 2 (µCHP Unit) to Energy Supply in BEVs and Buildings (Double Use Scenario)

The selection of the PCU performance depends on the demands of the customer and the corresponding application areas. The PCU concept should cover the BEV-demand completely, e.g. approximately 6 kW heat demand in compact class BEV with 4/5 seats according to Beetz et al. (2010). For this reason, the concept 7 with 2 kW_{el} (see Figure 9) has been chosen for prototype development. Because this concept can provide the BEV with approximately 6 kW heat power during the PCU operation 2 (µCHP unit with heat and power) and up to 11 kW heat power during PCU operation 3 (heat, cold and power). As far as the mobility (application in BEVs) is concerned, the PCU with the operation 2 (µCHP unit), as in the concept 7 with 2 $kW_{el,}$ is not oversized.

There are several application scenarios of the PCU. For example, during the drive (mobile) or when stationed in buildings. It is effective to load the BEV-battery during the stationary use and supply the house with heat energy to keep the energy losses as low as possible. In extreme cases, for example in winter, the building needs heat energy while a BEV needs the electricity too. For this application scenario, it is useful to take the PCU operation 2 (µCHP unit, see equation 2) to generate the electricity and the heat energy.

There are several types of users with different houses and BEVs. In this scenario, the BEV Volkswagen e-Golf and a building as follows are considered. The energy content of the battery at Volkswagen e-Golf is given with 21.2 kWh (Volkswagen Group of America, 2015). Due to available results on heat demand, a household with three persons (two adults and one child) in Miesbach (southeast of Munich in

Germany) is considered, which has a base area of approximately 150 m² (with year of construction 1967). One day in February 2012, there was an average ambient temperature of -10 °C, while about 80 kWh/day (generated with the stationary micro-CHP unit) heat energy was consumed (Lipp, 2015).

According to Rüscher et al. (2017), on average 13.5 hours are available to use the PCU in a house. Table 5 shows energy demands of the chosen house and the BEV (Volkswagen e-Golf) with the energy coverage from the PCU operation 2 (µCHP unit) and the excess energy. The result shows that the PCU operation 2 can cover the complete heat demand in a house of three persons and can charge the BEV-battery totally. The excess thermal energy up to 1 kWh can be used to preheat the passenger compartment of the BEV. The excess electrical energy up to 5.8 kWh can be used to supply the house or can be fed into the public power grid.

Table 5. *Energy Demands, Energy Coverage of House in Miesbach (2012) and Volkswagen e-Golf and Excess Energy due to PCU Operation 2 (µCHP Unit)*

Energy	**Scenario**				
	House (2012)	**BEV (Volkswagen e-Golf)**	**PCU operation 2 (µCHP unit)**		
	Energy demand [kWh]		**Energy supply for 13.5 h [kW]**	**Energy coverage [%]**	**Excess energy [kWh]**
Heat	80	-	81	100	1
Electrical	-	21.2	27	100	5.8

Mathematical Indicators and Comparison of the Portable PCU with Systems from the SOT

There are systems on the market, which can provide useable energies as well. These systems are the RE, power generators and stationary CHP units. However, not all of them are portable due to their high weight. These systems differ from the PCU in various respects. The RE and the power generators supply electrical power. Stationary CHP units additionally supply heat. The RE is applicable in BEV (power supply to increase range), power generators are used outdoors (e.g. power supply during camping) and stationary CHP units are used to provide buildings with demanded energies (for space heating and power supply). The PCU provides buildings with heat and electrical energy, while the BEV is provided with the cold air too.

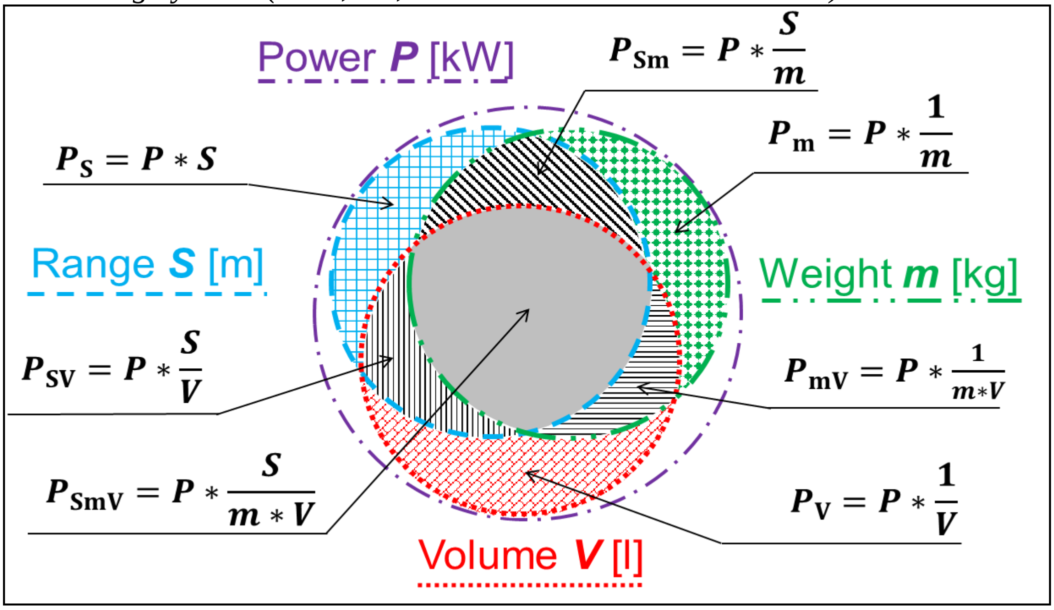
The comparison of different systems is made on the basis that these systems are used in a BEV and supply the BEV with their output energies (Baltzer et al., 2014; Bassett et al., 2012; Bouvy et al., 2012). To compare these different systems with each other, some indicators are needed. Figure 11 shows the basic variables and derived indicators as cutting sizes of basic variables. The circles represent the basic variables, which are the weight *m*, the installation space or volume *V*, the total power

P of an individual system and the additional range *S* of a BEV (e.g. Volkswagen e-Golf).

The range *S* is considered as a way, which can be achieved by a BEV with electrical power as output from the individual system only (e.g. RE, CHP unit and PCU). However, several systems can supply more than electrical power, as previously mentioned. Thus, all useable output performance *P* of a system is considered too. The power *P* of the PCU is the heat, cold and electricity.

Afterwards the comparison of different systems can be taken to classify them through the mathematical indicators. The intersections of basic variables reveal seven derived key figures. Some of these indicators are already known (Hanif et al., 2016) while others are new. The known indicators are P, m, V, S, P_m, P_{mV} and P_V. All the indicators, which contain the range *S*, are new. In this paper, the different power generating systems are compared with the new key figures, which consist of all basic variables (P, S, m and V). For this reason, the comparison is made with the indicators P_{sv} and P_{sm} (see Figures 11 and 12).

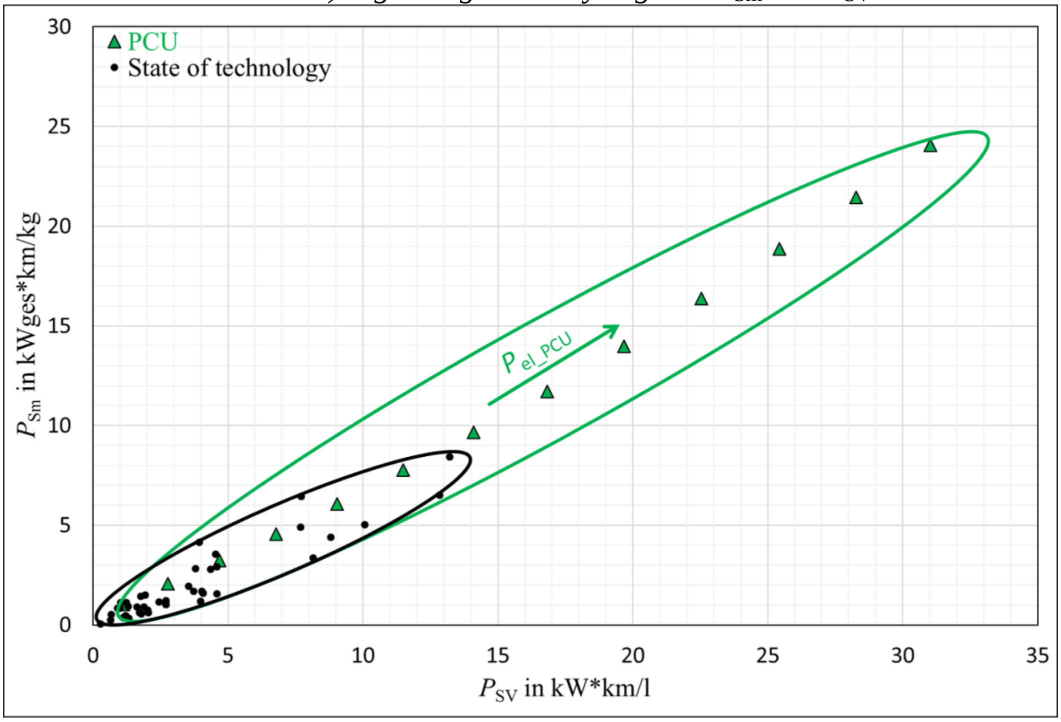
Figure 11. *Mathematical Indicators to Compare the Power (Electricity, Heat, Cold) Generating Systems (PCU, RE, CHP Unit and Power Generator)*



In order to determine the range *S*, the BEV Volkswagen e-Golf with its battery is considered to compare different energy generating systems. The battery of a Volkswagen e-Golf has a maximum rated capacity of approximately 21.2 kWh and can return maximum 190 km. Respectively, the Volkswagen e-Golf can drive a distance of 100 km with 12.7 kWh (Volkswagen Group of America, 2015).

This information can be used to calculate the range of the BEV with the respective or additional integrated power generating system. It should be noted that range detection is thus greatly simplified. In reality, the range of BEVs varies, for example, due to ambient temperature, temperature of the battery, charge level of the battery, route profile, driving style and consumption out of the battery or load (Geringer and Tober, 2012).

Figure 12. *Comparison of Different Power Generating Systems (PCU, RE, Power Generator and CHP Unit) regarding New Key Figures* P_{Sm} and P_{SV}



Source: (ICE and generator manufacturer, 2017).

Figure 12 shows that the PCU from 7 $kW_{el,}$ offers better values than systems of SOT regarding the indicators P_{Sm} and P_{SV}. The higher the PCU performance, the higher the indicators values are. The PCUs below 7 kW_{el} are similar to the systems from SOT, but the PCU offers following further advantages:

- Additional range for BEV
- Useful portable application
- Application in BEV, buildings and in further areas (e.g. leisure) possible
- Passenger comfort due to supply of heat and cold (in comparison to RE in BEV)
- Higher efficiency in comparison to conventional REs, power generators and stationary CHP units
- Higher BEV battery lifetime due to temperature control
- PCU useable as an emergency backup unit in BEV to avoid lying on the road (e.g. due to empty battery)

Therefore, the PCU concepts below 7 kW_{el} cannot be excluded. Rather, the concepts must be chosen according to the demands of the customer. Figure 12 is intended to present the current SOT and to encourage developers worldwide including the authors, to optimize existing and new systems regarding weight, volume and performance.

Conclusions

This paper shows a different way to develop a portable system (e.g. the PCU) with the new module design methodology. First, a mathematical model and performance of the system have to be defined. The PCU can supply the stationary (buildings) and the mobile (BEVs) areas with several energies (electricity, heat and cold). The module design methodology is developed for those systems which consist of several functional components. It takes developer-depended requirements and four analyses (package, distribution, modularization and interfaces) into account.

The module design methodology starts with the analysis, the package, to identify the main components of a given system (e.g. the PCU). The second analysis, the distribution, reduces the weight of the portable unit due to distribution components in possible application areas. After the distribution of components, the analysis of local and global interfaces is taken to eliminate non-functional concept variants. The analysis, the modularization, reduces the weight by splitting the portable unit package into several modules. The analysis of the local interfaces is carried out after the modularization in order to eliminate non-functional concept variants as well. This leads to several concepts of portable units (defined as µCHP units).

The relationship between performance, weight and volume for the three chosen concepts shows that the PU of concept 4 can supply up to 13.5 kW_{el} and is portable by two persons. Among the three preferred concepts, concept 7, which includes only two PU modules, has been chosen for prototype development.

During the µCHP operation, the PCU of concept 7 with 2 kW_{el} can charge the battery of the Volkswagen e-Golf totally and covers the heat energy demands in a house with three persons as well. Considering its volume, weight and performance, concept 7 can also be used in leisure. Furthermore, it can be easily assembled and disassembled due to a separate fuel tank.

Apart from the weight, volume and performance, the additional range of the BEV with an integrated PCU is also decisive. Several energy generating systems are available on the market, like range extenders, power generators and CHP units. To compare these different systems with the PCU, several new indicators are defined. In this paper, the new indicators (including range, power, weight and volume) compare the energy generating systems with the aim of adopting these in a BEV with usable output energies.

The comparison shows that the PCU offers better performance values from 7 kW_{el} upwards. However, the PCU with a power less than 7 kW_{el} cannot be excluded because it offers additional advantages such as battery temperature management, passenger comfort, higher efficiency (relative to RE), usability in further application areas (e.g. outdoors) and the additional BEV range.

List of Abbreviations

C	Compressor
BEV	Battery electric vehicle
CV	Concept variant

E	Internal combustion engine
Exh	Exhaust
ICE	Internal combustion engine
el	Electrical
G	Generator
HP	High pressure
IKME	Institute for Engineering Design, Mechatronics and Electromobility
MC	Main components
µCHP	Micro-combined heat and power
MDM	Module design methodology
M/G	Electric motor/ generator
PCU	Power conditioning unit
PU	Portable unit
RE	Range extender
Reg	Regulation valve
SOT	State of the technology
T	Fuel tank

List of Symbols

A_{wall}	Heat transfer surface of the liquid-air-heat-exchanger, m²
α_{air}	Heat transfer coefficient of the air current to the interior, W/m²/K
α_{f2}	Heat transfer coefficient of the heat transfer media (liquid/gas), W/m²/K
$\alpha_{\mathrm{heater\ wall}}$	Heat transfer coefficient of the heater wall, W/m²/K
H_{C}	Calorific value of fuel, Wh/kg
$c_{\mathrm{p,f1}}$	Specific heat capacity of the exhaust gas, J/kg/K
$c_{\mathrm{p,f2}}$	Specific heat capacity of the heat transfer media (liquid/gas), J/kg/K
J	Components per concept variant, dimensionless
k	Heat transfer coefficient, W/m²/K
m	Weight, kg
$\dot{m}_{\mathrm{f1}}$	Mass flow of the exhaust gas, kg/h
$\dot{m}_{\mathrm{f2}}$	Mass flow of liquid/gas, kg/h
$\dot{m}_{\mathrm{F}}$	Fuel consumption of internal combustion engine, kg/h
P	Total power of an energy generating system, W
$P_{\mathrm{el\_MG}}$	Electrical output power of generator, W
$P_{\mathrm{HP\_C}}$	Mechanical power of compressor to compress the refrigerant, W
P_{m}	Derived key figure, W/kg
$P_{\mathrm{m\_C}}$	Mechanical input power of compressor, W

P_{mech}	Total mechanical output power of internal combustion engine, W
P_{m_MG}	Mechanical input power of generator, W
P_{mV}	Key figure considered total power, weight and volume, W/kg/m³
P_S	Key figure considered total power and range, W*km
P_{Sm}	Key figure considered total power, range and weight, W*km/kg
P_{SmV}	Key figure considered total power, range, weight and volume, W*km/kg/m³
P_{SV}	Key figure considered total power, range and volume, W*km/m³
P_V	Key figure considered total power and volume, W/m³
Q	Quantity of components, dimensionless
$\dot{Q}_{f1}$	Output heat power of exhaust gas, W
$\dot{Q}_{f2}$	Output heat power of heat transfer media, W
$\dot{Q}_{chem}$	Chemical power of fuel, W
$\dot{Q}_{exh\_losses}$	Losses heat power of exhaust gas, W
$\dot{Q}_{exh\_warm}$	Heat power of exhaust gas, W
$\dot{Q}_{interior\_losses}$	Losses power of interior, W
$\dot{Q}_{warm}$	Heat power of the air current to the interior, W
S	Range of vehicle due to integrated power generating system, km
$T_{f1,in}$	Inlet temperature of the exhaust gas, K
$T_{f1,out}$	Outlet temperature of the exhaust gas, K
$T_{f2,in}$	Inlet temperature of the heat transfer media or liquid/gas, K
$T_{f2,out}$	Outlet temperature of the heat transfer media or liquid/gas, K
T_{air}	Temperature of the air current to the interior, K
V	Volume, m³
x	A part of P_{mech} to the generator, dimensionless
η_C	Efficiency of compressor, dimensionless
η_G	Efficiency of generator, dimensionless

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