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Methods to Determine Robust Innovation Paths for Electric Vehicle Technology

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Abstract

The following paper introduces a structured approach assessing the probability for the success of specific technologies increasing the endurance/autonomy of BEV's (Battery Electric Vehicles). Apart from range extenders, flow batteries (redox batteries as one variant) which might be refilled with electrolyte similar to conventional vehicles and technological improvements, the exchange of batteries is a method allowing BEV's similar ranges and similar usability like vehicles with internal combustion engines as they are currently used.

The suggested way for the investigation into the success of the concept holds a two fold approach:

Mapping the innovation: Enumerating the influencing factors

Assessing: In-depth research of acceptance

In step one influence analysis (causal loop) is applied to determine the most active factors and the system dynamics. In step two a multi criteria decision analysis is employed in order to quantify the potential impact of the factors/characteristics on the probability of the success of the concepts.

The two step methodology is presented for the battery exchange system (swappable battery), because for this system it is easiest to determine the technological aspects being purely mechanical and also the market impact based on the pre-existing knowledge of the facts. The range extenders and flow batteries still need technological research clarifying the operational characteristics of an industrialised concept before a robust assessment may be conducted. The paper anticipates the acceptance of the first mentioned concepts and enumerates the questions that have to be solved in order to allow a successful use case. The closing chapter analyses the influence of paradigm change on the assessment introducing uncertainties. In this respect it is shown how in depth foresight studies may reduce the risk for the innovator by introducing the actors/users introducing criteria for success and failure.

Keywords: taxation, marketing, BEV's

1 Introduction

The anticipated introduction of battery electric vehicles creates pressure on the public entities in terms of infrastructure needs and in terms of supportive policies The IEE ALTERMOTIVE project (www.alter-motive.org) aims at setting up policy recommendations analysing existing implementations and taking inductive conclusions guiding such policy decisions. One of the most important questions is how to avoid stranded investments for both forerunning vehicle buyers and entities building recharging or battery exchange infrastructure.

In contrast to internal combustion engines, with battery electric vehicles the autonomy is bought at a very high price in terms of cost and battery weight (e.g. secondary batteries which might be recharged). Therefore we see some proposals offering quick exchange for batteries. Whilst for electric assisted bicycles and electric scooters the battery exchange can be easily done by hand, for heavier vehicles the exchange might require investment in battery handling facilities.

Before investing in facilities whatsoever we propose to apply in-depth analysis in order to avoid stranded investment when missing technological or market developments. Apart from this natural resources may also be wasted by investing into battery systems which are not suited for the application but this is outside this analysis.

2 Methodology

With an unstructured approach one would analyse technological and market developments which may render the investment obsolete. But this approach would not account for the importance of the developments, e.g. the impact on the robustness of the approach.

In the first run the influence factors were depicted like on a mind map. Influences between the factors may are presented in a graphical way and weight attributed to them. The methodology created by Frederic Vester was to be applied on a sheet of paper and using paired analysis of the influence of issues on each other. The dominating influences may be identified and dynamics analysed in more detail when analysing causal loop diagrams. This way we can assess the system of factors not only with regards to reinforcing or balancing loops but also with regards to the timing. There is various software available to do the analysis in electronic form; the causal loop was developed with CONSIDEO MODELER. For the last step, the multi criteria decision analysis, spread sheets were utilized.

3 Mapping the scene

Battery exchange technology is a “non case” according to the uncertainty map presented by Pearson. The technological challenges might be mastered whilst the market acceptance is ambiguous. In this special case the supplier market is the problem because the investments lie in the battery exchange infrastructure.

In the first step the influences for the example of battery exchange technology for cars - not PEDELECs - have been researched. Some factors have to be explained:

- Market size: what demand might be caused by the offer?
- Macro-economic potential: creating jobs in the region
- Capital demand: need for financing
- Standards required: give the fact that more suppliers are serving the market – requiring the application of standards for interfaces vehicle–charging infrastructure
- Material resources needed: dependency on rare materials or costly traded materials
- Marketing-ability: possibility to roll out a campaign for all potential clients reducing the marketing cost
- Parking space available: to park one small electric or a standard sized car (parking space should be affordable - either shared or private)
- Taxation- consumption/CO_2: based vehicle tax
- Fees: road fees, parking fees…
- Local or regional purchase subsidies
- Access restrictions: ability to enter a defined zone (sensible area) – or during the night
- Incentives: ability to queue first, use high occupancy lanes, etc.
- Modular standard vehicles: detachable functional parts – thus reducing average size in use(future concept)
- Downsizing of vehicles in terms of size and weight
- Competitive range extenders: allowing extension of range at low investments in terms of money and weight – solutions might comprise fuel cells operated on liquid fuels, gas turbines, etc.

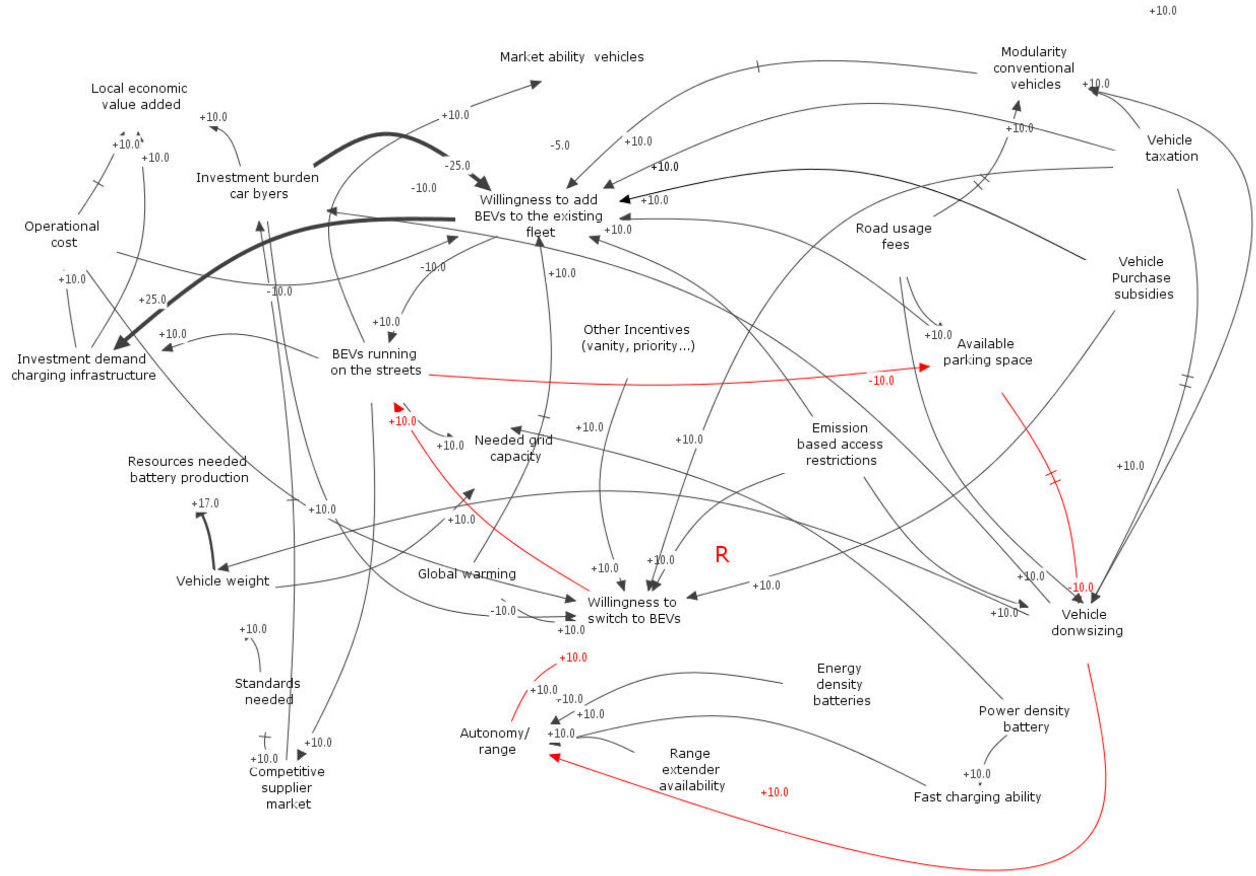

Figure 1: Causal Loop – Technological influences & Policies BEV's

The willingness to add BEV's to the existing fleet as well as the willingness to switch to BEV's is not only influenced in a linear way by a couple of factors but they are also embedded in some enforcing and balancing loops. Those loops comprise available parking space very often, which is at the heart of the street charging concepts. Secondly operational costs, which are created by depreciation of battery exchange/charging facilities are part of stabilized loops. For switching to BEV' light range extenders and increased autonomy caused by vehicle downsizing (indirect result from parking space limitations) are most helpful, and all of them might render battery exchange systems obsolete. A lot of incentives may act on downsizing of the vehicles and may therefore influence the system choice for recharging. The downsizing also influences autonomy/range for customers with a given investment budget for vehicle plus batteries. Leasing models are also affected indirectly by the investment cost in large battery packs.

If the battery size might be reduced with the help of low range BEV's added as second vehicle to the fleet and improvements of the energy density, the size of the handled batteries in the exchange stations would be smaller. Thus depending on the design the battery exchange stations might need a little less time per vehicle for their job.

But again, improved battery technology decreases the need for battery exchange. Categorising the factors in relation to the innovation hurdles delivers the following table:

Table 1: Hurdles and Success Factors

Hurdle	Factor
Economy of scale	Competitive supplier market
	Standards needed
	Resources needed batteries
	Investment demand infrastructure
	Theoretical demand BEV's
Product differentiation	Market ability
	Modularity of the vehicles
	Autonomy/range
	Vehicle downsizing
	Low vehicle weight
Switching ability	Local economic value added
	Available parking space
	Needed grid capacity
Legal & policy framework	Emission depending road usage fees
	Vehicle taxation
	Purchase subsidies
	Other incentives (priority)
	Emission-based access restrictions
Reference/show cases	BEV's running in the street
Technological know how	Energy density batteries
	light range extenders
Production know how	
Preferences consumers	Willingness to add BEV
	Operational cost users
	Investment burden car buyers
	Willingness to switch to BEV's
	Fighting global warming

The production know-how could not be linked to the incentives mentioned, this calls for additional incentives for industry to build on this know how setting up pilot actions for example. Rome's ATAC and other inner-city bus lines might be good show cases. Economic comparison might be applied for those cases, but do not influence the need for battery exchange in the exchange scenario. In case vehicles with internal combustion engines are to be replaced by battery electric vehicles because of expensive parking space in highly populated, but larger areas, battery exchange is essential.

4 Assessment of alternatives

To analyse the alternatives, scenarios were defined:

- Standard vehicle size BEV with battery exchange
- Standard vehicle size BEV with dual mode or range extender
- Autarkic operated BEV's with car sharing for longer trips
- Shuttled small BEV's on trains
- Fast charging
- HEV's having ICES's

For the multi criteria decision analysis, we also analysed the discussion in the internet at *autoblogreen* about the project *betterplace* before defining the weight scores.

The MCDA shows positive results for battery exchange, but only one scenario performs worse than battery exchange: fast charging, which has many unsolved problems regarding vehicle parking and battery lifetime. The state and municipal incentives however may cause a preference with users for dual mode or car sharing depending whether fees/taxes only apply in cities or also include vehicle footprint and are applied globally.

A second variant with battery exchange had to be introduced, because if standardisation fails having brand independent battery exchange, we may see proprietary solutions arising binding battery exchange to the dealers and repair shops of the big auto brands.

Table 2: Comparison of competing scenarios

Criteria	Question	Weight	Ranking					
	Ranking -3 to +3		Battery ex-change	Dual mode vehicles	Car sharing	Micro car Shut-tling	Fast char-ging	HEV/ ICE
Marketability	Does the concept allow roll out of effcient marketing campaigns for the sale of the vehicles?	10%	2	2	2	2	2	2
Investment demand car buyers	Does the concept overstress the willingness to invest in vehicles?	10%	1	1	2	3	3	2
Capital needed infrastructure	Does the concept overstress investments for infrastructure?	10%	1	3	3	1	-1	3
Sufficient grid capacity	Does the concept create problems in the grid?	10%	1	2	3	3	-1	3
Standards	Will there be a take up of battery charging interfaces and mechan-ical interfaces battery handling?	10%	1	3	3	2	1	3
Usability		*40%*						
	Usability "recharging"	4%	2	3	2	2	1	3
	Driving performance	4%	3	2	2	1	2	3
	Maintenance and Repair	4%	2	1	3	3	3	3
	Stowing capacity	8%	3	2	2	1	2	3
	Savety	4%	3	3	2	1	3	3
	Guaranteed ride home	16%	2	3	2	2	1	3
Parking space	Is the concept viable with regards to shrinking parking space in cities?	5%	2	2	1	3	2	2
Traffic flow	I the concept viable with regards to capacity on the roads?	5%	2	2	2	3	1	2
	Total	100%	1,8	2,3	2,3	2,1	1,2	2,7

Table 3: Comparison of standardised and proprietary battery exchange stations

Criteria	Weight		Ranking		Total	
	standar-dised stations	proprie-tary stations	standar-dised stations	proprie-tary stations	standar-dised stations	proprie-tary stations
Marketability	10%	11%	2	1	0,2	0,11
Investment demand car buyers	10%	11%	1	1	0,1	0,11
Capital needed infrastructure	10%	11%	1	0	0,1	0
Sufficient grid capacity	10%	11%	1	1	0,1	0,11
Standards	10%	0%	1		0,1	0
Alternatives	40%	44%				
	4%	4%	2	2	0,08	0,088
	4%	4%	3	3	0,12	0,132
	4%	4%	2	1	0,08	0,044
	8%	9%	3	3	0,24	0,264
	4%	4%	3	3	0,12	0,132
	16%	18%	2	1	0,32	0,176
Parking space	5%	6%	2	2	0,1	0,12
Traffic flow	5%	6%	2	2	0,1	0,12

The analysis shows that it is desirable to opt for standardisation of batteries and generic battery exchange systems. At large, the scores are positive for both variants. The big issue is that performance of battery electric vehicles (driveability) is much better having light battery packs. A modular system with regard to the battery pack size may allow car manufacturers to adapt it according to the vehicle needs – the comparison to the use of battery cells according EN 60086-2 and EN 60285 is obvious. With EDLC (ultracaps) the standardisation already has begun. Taking this development into consideration, the acceptance by the investors will be much higher since the high power stackable battery cells might not only be used in microcars (for larger cars the amount of cells which may be handled manually is to big at present) but also be used with other devices like lawn movers, e-scooters etc. - as a consequence of the market size and competitiveness the price of the cells will drop and the battery might be handled manually. While manual exchange looks only feasible with ultra-light vehicles, building mechanical change systems will also profit from the standardisation. A non standardised survey has revealed that potential buyers are partly inclined to buy microcars which may be operated with much smaller battery packs or have much higher autonomy.
Those microcars need significantly less energy (7.5 kWh/100km for a 7yr old 210kg vehicle having new 50Ah 36V LiFePO4 batteries) and thus also less investment in batteries.
Inspired by a user centre approach developed in the FP7 project U-STIR (http://www.u-stir.eu) we analyse the best ranked methodology the from the user perspective, which is depicted in Figure 3 – see below.
The topics are analysed in Table 4. The user centred analysis compared fast charging and battery exchange. The fast charging has some implications on the usability, requires less investment in batteries (in case of higher allowable C's when charging) and has strong impact on parking regulations and social acceptance.

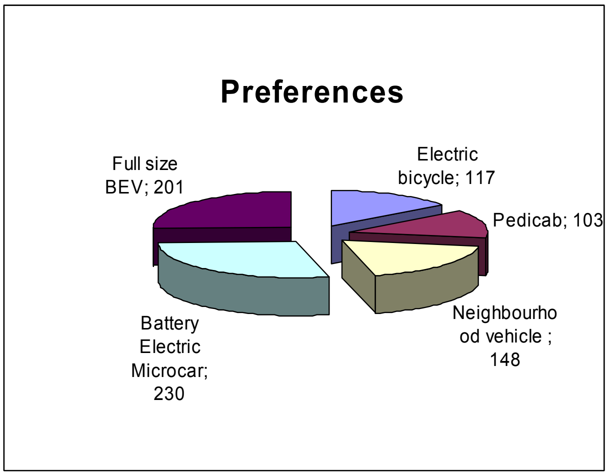

Figure 2: Preferences of potential buyers, source sugre 2008 www.greenfleet.info

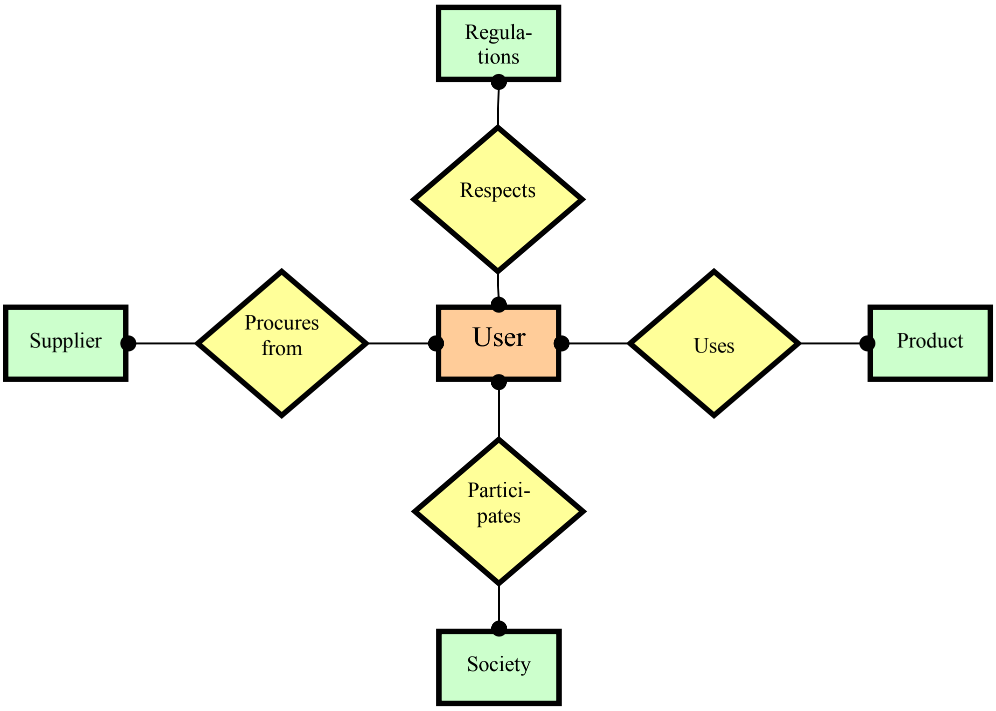

Figure 3: Entity Relationship Diagram: User centred aspect of innovating (simplified)

Table 4: Comparative Assessment (1=best 5=worst)

Category	Subcategory	Comparing	Battery Exchange	Fast Charging
User acceptance	Info transfer	Both methods may be communicated well, battery exchange might follow better the model of refuelling stations in terms of time needed	1	2
	Time needed to convince	Fast charging stations might be seen as quicker to erect	2	1
	Stability of the acceptance	Investment decision may stay for a longer period of time	2	2
Availability technology	Info transfer (spec.)	Problem is well understood	1	1
	Time needed for RTD	Problems may be mastered without quantum leap	1,5	1
	Stability of the solution	Charging has a better technological potential (EDLC)	1,5	1
Business model Operator/Supply	Info transfer	Fast charging is nearer to a fuel company business case, so easier to be understood	1,5	1
	Time needed setting up business	Building robotic exchange may take longer	2	1
	Stability of the business model	Fast charging has more technological potential	2	1
Acceptance environment	Info transfer	Separate parking lots needed for charging	1	3
	Time needed to convince	Battling is quite usual for parking space in cities	1	3
	Stability of the acceptance	Policies are understandable and logic	1	2

Comparing battery exchange and fast charging the quantification gives the following picture with regards to the main categories (centre = better):

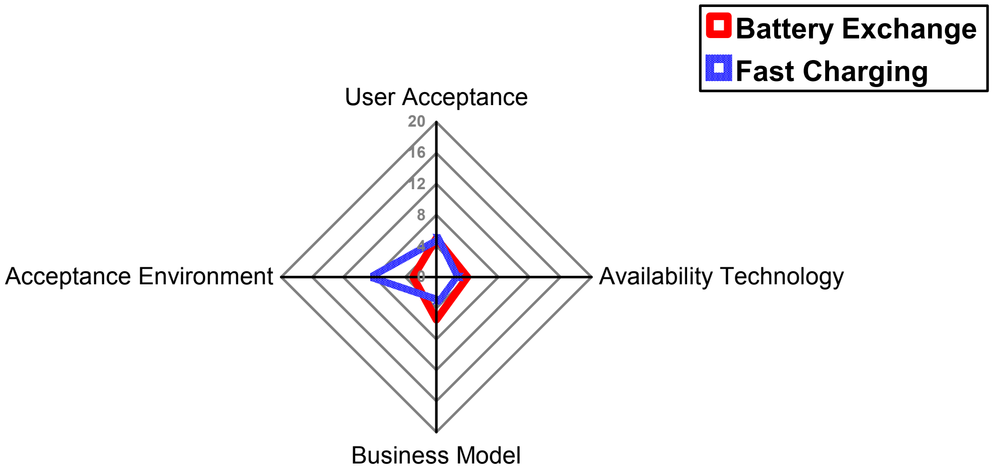

Figure 4: Overview of the assessment in the 4 dimensions (centred=better)

The assessment shows that fast charging may be regarded as equal and better in three dimensions, but fails in terms of acceptance of the environment. This might not be the case for taxis or buses or delivery trucks already having their defined parking areas but for passenger cars this is certainly creating envy. For private operators of parking facilities this question is even more relevant. We also have examples where cities refrain from advertising existing cost reductions of parking fees for electric vehicles – may be fearing to loose money. So what might be proposed for improving the concept of fast charging is to investigate potential to have a larger roll out of charging stations allowing vehicle placement so they do not require blocking the parking space solely for electric vehicles. Private experience with hanging leads from 2nd floor allowing flexible vehicle placement were positive so far.

5 Other factors and uncertainties

Apart from analysing existing solutions which may be tested in reality or easily imagined, there are potential future solutions which may allow increase of autonomy. The Austrian project PIA paradigm change in propulsion techniques which is funded by the Austrian FFG in the A3PLUS Programme initiated by the Austrian Ministry for Transport, Innovation and technology will be validating the new concepts – see table 5.

One very important factor when analysing emerging technologies is the compatibility with existing standards, both in terms of technological standards and existing supply chain standards – in terms of module integration and tier1 – assembler co-operation.

The quick analysis shows that some concepts are lacking attractiveness (in italics). For two concepts, the operational motor stress control and the pluggable energy storage, the anticipated user reaction shall be kept in focus in the development phase. The assisted foresight driving might be seen as optional tool in order to avoid negative reactions. But this will not allow asking for a higher vehicle price, so governmental incentives are needed to ease introduction.

6 Summary

The analysis of the factors influencing the robustness of the decision investing in battery exchange infrastructure has brought new insight which factors might endanger the robustness of the decision. It seems to be valuable to investigate inter dependency of policies and technology roadmaps before taking the decision to invest in one recharging technology infrastructure. The most feasible scenario does not exist as such, but is influenced by the lay out of the incentives for clean vehicles. So policies might drive the prevailing technological solution. Especially the policy supporting downsizing of vehicles and thus increasing autonomy with given investments in batteries may render the battery exchange technology obsolete partly.

The analysis is helpful for all approaches which are bound to a liberal market, but might not be helpful where dominating market actors may impose a solution. In this case other problems may prevent success – e.g. technology gaps may introduce massive correction costs. The stronger the anticipated customer reaction, the costlier it will be to implement a solution

Table 5: Technical description of innovative concepts

Concept	Objective Technical Description
Use of waste energy	Use of waste energies with electric vehicles having no big waste energy source (no ICE). Both controller and motor are potential sources of heat to be used for heating up the battery on cold days
Use of environmental energy	Use of environmental energies with electric vehicles having no big waste energy source (no ICE). Surfaces on cars may be equipped with solar absorbers in order to preheat the batteries if needed, photovoltaic panels might not be efficient for heating but ventilation and cooling.
Operational motor stress control	Light electric motors which are controlled in operational to extend service lifetime. Temperature excursions with copper wire isolation and demagnetisation of rare earth magnets shall be avoided by sensing and control.
Modular power trains	Modular range extender concepts, with ultra-light vehicles having very low power demand both the retrofitting of fuel tanks for range extenders and also inserting of additional range extenders is possible.
Functional body structures	Integration of functions into the body structure. Casings for batteries or fuel storage are one variant, the others might be connected to heat management systems.
COG adaptation	Power train tilting. With non tilting ultra-light vehicles, the centre of gravity might be changed allowing faster turns. This comprises dynamical (precession forces) but also static components (actuation) of the COG.
Foresight driving	Energy saving driver assistance. In the first step the power generator is decoupled from the throttle (serial hybrid power train), in the second step an automated throttle is introduced.

Table 6: Assessment of innovative concepts

Concept	**Qualitative engineering assessment** (availability of techniques, feasibility)	**Assessment of non technical factors** (usability)	**Estimated timetable for deployment**	**Likelihood of commercial introduction** (success business model)
Use of Waste energy	storage of battery heat feasible, controller and motor heat losses are small in size and generated to late	No problem envisaged	Half a year	Very likely
Use of environmental energy: solar thermal	*Only feasible in climates with high insolation and cold ambient temperatures, might be integrated with A/C*	*Problematic if battery temperature is prioritised over interior temperature*	*Far*	*Unlikely*
Use of environmental energy: photovoltaics	Higher yields with expensive cells, energy amount restricted	No problem envisaged	Already on the market	Very likely
Operational motor stress control	Embedding of sensor in rotating elements problematic, wireless sensors preferred	**User may react adversely to interrupted acceleration force**	A couple of years	Likely
Modular power trains: range extender	*Flip in solutions may have separated energy storage – rolling solutions preferred*	*Garages necessary to store is away*	*Very far*	*Unlikely*
Modular fuel tanks	Save connectors and locking mechanism needed	**Weight and safety concerns**	Far	Likely with high energy densities
Functional body structures for heat management	Reinforcement needed where inlet and outlet are located	Vibration/Noise insulation needed	Near	Likely
Functional body structures for energy storage	*Separation of inner pressure withstanding function and sealing necessary*	*Safety concerns*	*Far*	*Unlikely*
Centre of gravity COG adaptation power train static	*COG adaptation may be an issue for off-road vehicles*	*Unexpected actuation may raise concerns about structural problems*	*Far*	*Unlikely*
COG adaptation power train dynamic	*Basic technology to be developed*	*Side effects?*	*Very far*	*Unlikely*
Assisted foresight driving (automated throttle)	User shall be able to overrule the system easily, mature sensing necessary and good GPS enabled maps	**Driver sovereignty decreased?**	Medium term	Likely for information systems in the first run

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