Registration form (basic details)

1a Project Title

Car as Power Plant - Fuel cell cars creating an integrated, efficient, reliable, flexible, clean, multi modal and smart transport and energy system.

1b Project Acronym

CaPP (Car as Power Plant)

1c Principal investigator

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2 Summary of research proposal (max 250 words)

The fuel cell car as power plant, a paradigm changing concept, proposed by Prof. dr. Ad van Wijk, has the potential to replace all electricity production power plants worldwide, creating an integrated, efficient, reliable, flexible, clean and smart energy and transport system. The concept is that fuel cell cars do not only contribute to a more efficient and cleaner transportation, but that when parked they can produce electricity more efficiently than the present electricity system and with useful ‘waste’ products heat and fresh water.

In terms of technology, the energy production system can be envisaged as a fleet of fuel cell vehicles, where cars while parked (over 90% of the time) can produce with the fuel cell electricity, heat and fresh water, which will be feed into the respective grids. From a social perspective the stakeholders directly and indirectly involved in the design, building and operation of such a system, are car park operators, the local power, heat and water distribution companies, gas suppliers, H₂ producers, the equipment, system and software manufacturers but also municipalities, regulators, policy makers and not to forget the car owners/users.

This project investigates the feasibility of hydrogen fuel-cell car system to design a detachable decentralized multi-modal energy system. The scientific challenge is in shaping, controlling and operating such a socio-technical system of Car as Power Plant representing integrated energy and transport system that is economic, efficient, clean, robust, and reliable with minimal societal costs over its life cycle.
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3 Main field of research (compulsory)
code + main field of research (give only one main field of research):
14.90.00 Technology, other

code + other field of research:
16.20.00 Software, algorithms, control systems
14.30.00 Electrical engineering

4 Composition of the Research Team (maximum 1200 words)
The research team will consist from researchers from three different faculties of the Delft University of Technology and the University of Utrecht, i.e.:

Dr.ir. Zofia Lukszo (Z. Lukszo), Associate Professor, Delft University of Technology, Faculty of Technology, Policy and Management, Section Energy and Industry

Prof.dr.ir. Bart De Schutter (B. De Schutter), Full Professor, Delft University of Technology, Faculty of Mechanical, Maritime and Materials Engineering, Delft Center for Systems and Control

Prof. Dr. Ad van Wijk (A.J.M. van Wijk), Part-time Professor, Delft University of Technology, Faculty of Applied Sciences, RST/Radiation, Science and Technology, Fundamental Aspects of Materials and Energy.

Prof. Dr. Kornelis Blok (K. Blok), Part-time professor, Utrecht University, Faculty of Geosciences, Copernicus Institute for Sustainable Development, Energy and Resources Group

3 full-time PhD candidates (have to be recruited) and one part-time three-year post-doc, they will be jointly supervised by the four above-mentioned senior team members.

Dr.ir. Zofia Lukszo studied applied mathematics at Technical University of Lodz and philosophy at University of Lodz, Poland. In 1996 she received at the Eindhoven University of Technology, the Netherlands, the Ph.D. degree for the thesis "A Practical Approach to Recipe Improvement and Optimization in the Batch Processing Industry". Since 1995 Zofia has been working at the Faculty of Technology, Policy and Management at the Delft University of Technology, the Netherlands. She is there an Associate Professor in the Energy and Industry group. Her research focuses on operations management, mainly in the energy infrastructure sectors and the process industry. She is a leader of the programme Intelligent Infrastructures (12 fte) within an international research programme on Next Generation Infrastructures http://www.nextgenerationinfrastructures.eu/. The Intelligent Infrastructure programme concentrates on a wide range of problems in the way infrastructures are functioning today, and aims to develop new, intelligent concepts for modelling, optimization and control of their operation resulting in more effective, efficient, safe and reliable utilization. Zofia Lukszo is frequently a member of the International Program and Organizing Committee of international conferences. She has run several EET, BSIK and EU projects with several partners from industry, including Unilever, TNO, Enexis, Eneco, INDRA (Spain), and Transelectrica (TSO Romania). In addition, she is managing director of the journal Infrastructure Complexity, Springer, ISSN: 2196-3258. Since 1 September 2013 she is a director of the
Master Program System Engineering, Policy Analysis and Management (SEPAM) at Delft University of Technology.

Prof. dr.ir. Bart De Schutter received the PhD degree in 1996 from K.U.Leuven, Belgium. In 1998 he moved to Delft University of Technology where he currently is a full professor within the Delft Center for Systems and Control. Bart De Schutter has an extensive expertise in research on management and control of transportation and infrastructure networks (including electricity networks), model-based predictive control, control of hybrid systems, and multi-agent control of large-scale complex systems. In 2003 he obtained a VIDI grant on the topic of multi-agent control of large-scale hybrid systems from the Dutch Technology Foundation STW. One of the applications of this VIDI project involved multi-agent control of electricity networks. Bart De Schutter has published 2 books and 99 international journal papers (WoS H-index: 16), and he was the coordinator of an EU FP7 project on model predictive control for large-scale systems (HD-MPC). He has run several NWO, STW, BSIK and EU projects with several partners from industry, including Shell, Siemens, Technolution, TeNNeT, TNO, Witteveen+Bos, and EDF (France). In addition, he is associate editor for Automatica and IEEE Transactions on Intelligent Transportation Systems.

Prof. dr. A.J.M. van Wijk studied Physics at the Utrecht University and is sustainable energy entrepreneur and part-time Professor Future Energy Systems at TU Delft. Van Wijk started his career as scientific researcher in sustainable energy at Utrecht University. In 1984, van Wijk founded the company Ecofys, which eventually grew into Econcern. Econcern developed many new sustainable energy products, services and projects, and performed many energy system scenario studies. Examples include the 120 MW offshore wind farm Princess Amalia in the North Sea, several multi-MW solar farms in Spain and a bio-methanol plant in the Netherlands, which is the largest second generation biomass plant in the world. Van Wijk achieved many important prizes for excellent entrepreneurship. Amongst others he was Dutch entrepreneur of the year in 2007 and Dutch top-executive in 2008. At TU Delft van Wijk focuses on the energy systems of the future. Especially he will do research and at the same time will realize “the Green Village”. Prof. A. van Wijk has directed research and utilisation successfully. To name only a few direct drive offshore wind turbine technology (Darwind), wind prediction services, innovative solar roof-mounting systems (Consoles and InterSoles). BioMethanol production from glycerine.

Prof. dr. K. Blok studied experimental physics at Utrecht University and received a Ph.D. degree in 1991 on a thesis ‘On the Reduction of Carbon Dioxide Emissions’. At Utrecht University he holds a professorship in Sustainable Energy and is supervising the master programme Energy Science. In 1984 he was one of the founders of Ecofys, where he is now Director of Science. Kornelis Blok has all-round research experience in the field of energy efficiency improvement and clean energy production. He delivered important contributions in areas such as industrial energy efficiency, effectiveness of energy efficiency policies, renewable energy systems, carbon capture and storage, international climate regimes, hybrid energy analysis, and marginal abatement cost curves. He played an important role in the development of European energy policies and international climate policies and has worked in many countries around the globe. He authored and co-authored about 100 articles in peer reviewed scientific journals, several books and 250 research reports, conference contributions and other scientific publications. He was a lead author for the Third and Fourth Assessment Reports of the Intergovernmental Panel on Climate Change, the institution that was awarded the Nobel Peace Prize in 2007. With his company he won the Erasmus award for the most innovative company of the Netherlands in 2008.

dr. L. Verhoef (intended post-doc) studied experimental physics at Utrecht University and received a Ph.D. degree in 1990. He has worked in industry, government and consulting, mainly on innovation and
paving the way for large scale introducing of disruptive technologies, such as: SunCities: the first suburb fully developed to optimize solar energy [32], energy from the desert, an IEA funded 10 year study to supply the worlds’ electric power (also by Hydrogen as a carrier) from deserts covered with solar panels [33], and Minewater, a EU funded project to convert Europe’s mine regions into sustainable suppliers of heat, by pumping heat out of the water-filled abandoned depleted coal mines in Europe. He has held numerous workshop and conference presentations and published books and papers on these topics. He has been working as a science and innovation officer on the Car as Power Plant since 2011.

**Industrial involvement**

The research team group has a long-standing tradition concerning industrial involvement in the applied research.

Shell supports the project. Prof. dr. Gert Jan Kramer, Manager Energy Futures, Shell Global Solutions International BV, confirmed a strong substantive interest in the project, the letter of support is attached.

Moreover, seven other companies/organization confirmed specific interests in this project in letters of support. The seven firms selected not only share a common interest in the central research objective, but each also has a company-specific interest in the research results. They will be a member of the user committee of the project and/or will participate in case studies for testing methods and prototype tools developed in the project.

Besides Shell, the following companies are involved:

- GasTerra (International natural gas trading company; contact person: Gerard Martinus, Energy transition manager)
- Eneco (Power company; contact person: Glenn Bijvoets, Energy transition manager)
- Stedin (Energy infrastructure company; contact person: Guy Konigs)
- BAM (Construction Company, contact person: Nils Beers, business development manager electric transport)
- Q-Park (car park operator; contact person: H. Pot / Mark van Haasteren, CEO)
- HyTruck (hydrogen fuel-cell powered vehicles, contact person: Eric Beers)
- The Green Village (TU Delft’s entrepreneurial future sustainable systems real life test environment; see ‘Welcome to the Green Village’ [29] [www.thegreenvillage.org](http://www.thegreenvillage.org); contact person: ir. Chris Hellinga, senior scientist [chris.hellinga@thegreenvillage.org](mailto:chris.hellinga@thegreenvillage.org))

**5 List of key publications**


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6 Research School

The research will be conducted at the Delft University of Technology, at the faculty on Technology, Policy and Management (TPM), Mechanical, Maritime and Materials Engineering (3mE) and Faculty of Applied Sciences, with close cooperation with Utrecht University, Faculty of Geosciences, Copernicus Institute for Sustainable Development. In addition, the PhD student at the Delft Center of Systems and Control will also participate in the national research school DISC (Dutch Institute for Systems and Control, http://www.disc.tudelft.nl).

Via Utrecht University, the research will also be connected to SENSE, the Netherlands’ research school for Environmental Sciences (www.sense.nl).

Interaction with industry innovators and testing will be facilitated in The Green Village (www.thegreenvillage.org), a 100% subsidiary of TUD [29]. The Car as Power Plant forms one of three pivotal Future Lab programmes of the Green Village, embedded in the Delft Energy Initiative, (www.tudelft.nl/en/research/energy/), representing about 700 energy researchers of TU Delft. The Green
Village concept unifies clever, imaginative strengths of scientists and entrepreneurs and turns ideas and visions into experiences and commercially viable products and services.

Research proposal

7 Content of the proposed project
The research will be done through 4 interacting and complementary research projects involving technology, customer, control, socio-technical and business aspects. We will:
- design, assess and analyse the fuel cell car as power plant (CaPP) in integrated transport and energy systems (PhD 1),
- investigate and design robust control systems of CaPP-based smart energy systems (PhD 2), and
- explore effective incentive and organizational structures for the emergence of CaPP integrated energy and transport systems (PhD 3).
Furthermore, we include an integrating post-doc project aimed at developing business models for CaPP systems (post-doc).
In parallel, a demonstration project is being set up in The Green Village to develop technology, system integrations, smart control strategies and trade models which will serve as a test ground for the CaPP integrated transport and energy systems.

7a Scientific aspect
Fuel cell cars can replace worldwide all large scale power plants because of the following:
Fuel cell cars have potentially a higher efficiency in converting gas via hydrogen into electricity than the average electricity system efficiency.

On average cars are used below 10% of the time, which implies that fuel cells in the car can be used over 90% of the time for electricity, heat and eventually fresh water production.

Nowadays, worldwide installed electricity production capacity is about 5.000 GW. However, every year 80 million new cars are sold. The average new car engine capacity is about 100 kW, which implies that yearly 8.000 GW electricity production capacity on wheels is sold.

A 100 kW fuel cell in a car can produce all the electricity for about 100 Dutch households. A car park with 500 fuel cell cars is a 50 MW power plant that can supply electricity to all households of a city like Delft.

Hydrogen can be produced from natural gas, e.g. by steam reforming or from electricity by electrolysis at the gate of a car park or near other parking places. Therefore there is no need for a new hydrogen infrastructure.

The idea that the fuel cell car is not only used for transportation but also for electricity, heat and water production, is a paradigm change, recognized by the World Future Society, who ranked this concept first in the recent Forecast 2013-2025 [1]. The question is how such an integrated and connected transport and electricity production system can be realized. Of course there are many technological, environmental, economic, social and political challenges. In all of these areas research and development is necessary. The research and demonstration proposed will explore the overall car as power plant system and perform research into the critical system issues.

The project is the follow-up to the successful exploratory and feasibility study, including the first demonstration done by the Green Village (see the figure above). The scientific contribution to be realized in three interacting PhD and one post-doc research projects is as follows:

**PhD 1: Design, assess and analyse the fuel cell car as power plant (CaPP) in integrated transport and energy systems**

The research question of this subproject is:

"How can we design and develop an integrated transport and energy systems based on fuel cell cars that produce electricity, heat and water also and how can it be integrated into the energy and transport domain in different growth and technology development scenario’s?"
The CaPP technology is part of various systems: the electricity system, the fuel system and the transportation system. Therefore, a systems analysis approach is necessary to determine the role that CaPP can play in the total energy system and to optimize that role (in terms of energy, costs and environmental impact).

The impact of CaPP will be analysed, working from a global integral perspective, and optimized using the following research methods:

1. System design and system analysis to determine technology developments and their environmental and economic impacts. This includes technology analysis, environmental analysis and economic analysis; learning/experience curves and technology forecasting, cost-benefit analysis and input-output analysis.
2. Electricity and transport system modelling and simulation, determining the impact of power production by the CaPP system on the electricity system and the impact of fuel (hydrogen) on the transport systems.
3. Scenario analysis of possible development pathways of CaPP.

The potential of these methods:

Ad 1. Valuation models with indicators on cost, but also value and value optimization will be developed. The economics of producing electricity from grid-connected fuel cell cars in commercial settings potentially supplying electricity at competitive rates will be investigated, including the cases when it produces significant annual benefits, for instance energy balancing services and local production [31]. Furthermore, experience curve analysis will be used to forecast costs of the technologies involved in the future. In the past we have shown that demand and renewable energy supply technologies show declining prices and costs at an average learning rate of 18 ± 9% [23, 25]. Uncertainties in the Car as Power Plant concept will be identified and minimized.

Ad 2. We will use existing models on elements of the energy infrastructure, both detailed engineering (such as Cycle Tempo\(^1\)), and global scenarios such as Shell’s NEW LENS, and using model based design tools (MATLAB, SIMULINK) to fill the missing links and connect the modules.

Ad 3. Energy scenario analysis will be used as a tool for disruptive but feasible technical solutions offered by the Car as Power Plant. An example: recent application done by the University of Utrecht resulted in a plan presented in the framework of the Intergovernmental Panel on Climate Change and of the United Nations Environment Programme report ‘Bridging the Emissions Gap’ for twenty-one coherent major initiatives could together stimulate sufficient reductions by 2020 to bridge the global greenhouse-gas emissions gap [22]. Another study using forecasts demand and supply energy scenario shows that a global energy system by 2050 which derives 95% of its energy from sustainable sources following an ambitious, but feasible pathway, based on currently available technology and realistic deployment rates [24]. In the scenario studies, energy flows will be characterized by carrier type (electricity, heat and fuels), existing technologies, learning curves, and disruptive, integrated systems embedded in the Car as Power Plant concept.

This subproject results in a full assessment of the CaPP system, and an improved understanding of and new insights in the interaction with the electricity, fuel and transportation systems.

\(^1\) Cycle Tempo (www.cycle-tempo.nl), is a TU Delft developed tool for the thermodynamic analysis and optimization of systems for the production of electricity, heat and refrigeration.
PhD 2: Robust control of CaPP-based smart energy systems

The research question of this subproject is:

"How to determine in an efficient way the optimal time instants for charging or discharging the fuel cells as well as which energy source to use or to convert while taking into account the variations and uncertainties in the demand and supply of energy?"

To address this question we propose to use a model-based predictive (MPC) control approach \([27, 28]\) that takes into account both the current charge state of the fuel cells as well as predictions about future energy needs, production capabilities of the renewable power sources, energy prices, etc. for the next few hours or days. Such predictions are often characterized by one or more base profiles around which the actual values may vary, and in many cases stochastic information is available on the likelihood of each base profile to occur as well as the variations around the base profiles. By combining this information with models that describe the charging/discharging processes, the storage and conversion processes, and the generation of energy, we will develop a so-called robust MPC approach to adequately manage the CaPP-based Smart Energy System. The main scientific challenges are (1) the derivation of base profiles and the corresponding stochastic information (this should also include the potential changes in behaviour of the users due to the presence of the Smart Control System), (2) the development of new robust MPC approaches that can also deal with the hybrid nature of the system (i.e. the combination of continuous dynamics (e.g., currents, voltages, energy levels) and discrete-event behaviour (e.g., switching appliances or power sources on and off, changing the type of energy sources, activating a certain type of energy conversion)), and (3) the development of fast and efficient numerical algorithms for robust hybrid MPC to make it suited for real-time control.

The research methods that we will adopt to address the challenges outlined above include: model-based estimation and control approaches \([27,28,19]\), robust control methods \([14,15]\), distributed control \([KP3,12]\), mixed-integer optimization (to deal with the hybrid behaviour \([KP1,KP2,16]\)), and on-line (distributed) optimization methods \([KP4,KP5]\).

This subproject will result in new efficient and robust control methods for CaPP-based Smart Energy Systems.

PhD 3: Exploring effective incentive and organizational structures for the emergence of a CaPP system

The research question of this subproject is:

"How can a detachable decentralized multi-modal smart energy system be shaped and organized into a sustainable system, taking into account "what-if" scenarios in an uncertain dynamic, multi-actor and multi-objective world?"

The objectives of this subproject are to address the compelling technical, operational and institutional challenges of CaPP system by exploiting the analytical power of cutting-edge agent-based modelling and simulation (ABMS) technology. ABMS is a category of advanced modelling and simulation tools particularly relevant for cross-sectorial and inter-disciplinary research on complex adaptive systems exhibiting both technical and social (multi-actor) complexity. ABMS is the premier candidate with which to model socio-technical systems and explore how structural and behavioural changes unfold from the
interactions between agents (representing actors) within and between the social and the technological networks. This research aims at combining state-of-the-art developments in agent-based modelling and simulation with technical insights and models developed in projects PhD1 and PhD2 to create a simulation tool for understanding and shaping the emergence of the CaPP system. The tool will be used to systematically explore the (combined) effect(s) of different incentives targeting different actors in the desired system.

Its purpose is to learn how to influence the emergence and development of the CaPP system, and to investigate which (constellation of) incentive system(s) is/are most likely effective to bring such systems into being. The challenging aspect in this study is using the so-called MAIA methodology (Modelling Agents based on Institutional Analysis) to reflect the social and institutional structure. Another challenging aspect concerns the use of decision models based on regret minimization. Moreover, as customer experience determines a large part of the success of the project, socio-psychological theories (a.o. "Theory of Planned Behaviour") will be examined to investigate to what extent the behaviour of customers, involving not only the economic but also social and ecological aspects, play a role in the accepting and usage of the CaPP technology.

The research methods: Agent-Based Modelling [KP6, 6, 7, 8], MAIA methodology [9], No-regrets approach [10], Theory of Planned Behaviour [11].

This subproject results in an agent-based simulation tool to investigate the emergence of a CaPP system in a highly uncertain environment.

**Post-doc integrating project: Business models for CaPP**

The research question of this subproject is:

"What are the most promising business models for the CaPP system in the (Dutch) energy and transportation system, and what are the related implementation barriers and solution strategies?".

The success of the implementation of the CaPP system is mainly dependent on the business models and strategies of the actors involved. The interrelation between technology, strategy and business models will describe how actors can increase their competitive positions. The challenge is on adding value to the knowledge on how technology, strategy, customer interface and business models should be intertwined to build a sustainable business and/or service for CaPP in the Dutch energy and transportation sector. As such, this action will integrate and synthesise the findings from PhD 1 – PhD 3, and foster the interaction between these and the companies and other stakeholders involved.

The research methods: stakeholder analysis and business model theory.

This post-doc project results in the definition and evaluation of the most promising business models from the perspective of different stakeholders.

For the overall project, it should be stressed that a consistent principle in managing the transitions to future energy systems is to increase **flexibility** – flexibility in the energy sources, in the generation/consumption technologies, and in the spatial and temporal dimensions of supply, demand and pricing. The emphasis in this project is on modelling, analysis, control and institutional design of such complex future energy system as CaPP. At the same time, the proposal addresses important public...
values such as security of supply, efficiency and affordability, and investigates business model to bring the concepts into being.

Therefore the proposal contributes to the following themes of the call:

1. Systems for control, management, and reduction of uncertainties in Smart Energy Systems (SES) (in particular, the development of control tools for supply/demand matching; energy management at individual consumers and producers; monitoring, managing, and controlling the state of the SES)
2. Tools for analysis, development, and maintenance of SES (agent-based simulation tool to investigate the emergence of a CaPP system)
3. Behavioural uncertainties (agent-based simulation tool used to explore novel institutional arrangements depending on uncertain preferences and behaviour of customers)

7b Innovation

This project proposes a fundamental (paradigm) change for design and operation of future energy and transport systems. The Car as Power Plant (CaPP) will result in an integrated transport and energy system, especially electricity system. The conceptual ideas and system innovations will result in

- CaPP will be a more energy efficient system. The CaPP system has a better energy efficiency in both transport as well as electricity production, resulting in substantial fuel savings and therefore also less carbon dioxide emissions.
- CaPP will be a more reliable energy system. Instead of large power plants positioned far from the load centres, many small and very flexible fuel cell cars produce electricity close to the electricity and heat demand, resulting in a highly reliable and robust electricity system.
- CaPP will be a more economic energy system. Nowadays investments in power plants have to be done, but in using the fuel cells in cars as power plant the investments in electricity production capacity are already done, resulting in less investments in the total transport and electricity production system.
- CaPP will improve the local environment. Fuel cell cars do not produce exhaust gasses, only water vapour and the fuel cell does not produce noise.

The proposed research itself is about an innovative system concept and will give direction to many innovative new technologies, systems, products, services, infrastructural innovations, business concepts, organisational, regulatory and policy innovations.

Since the subject of research, the car as power plant, is really a paradigm changing concept, the research topic is new and no (scientific) publications are found in the literature. However, the research methodologies are state of the art and used in many other research fields.

7c Utilisation

1. Description of the problem and the proposed solution.

The research into this paradigm changing concept will result into (directions for) the development of new technologies (e.g. efficient technology for hydrogen production from natural gas, heat recovery from fuel cells, automated parking, hydrogen fuelling systems, ...), systems (car park power plants, control systems for energy production, systems for automated parking, billing, servicing) or new services (new service and business concepts for energy companies, energy service companies, garages, car park operators, software providers, gas/hydrogen producers/distributors, ...). The research will give also
directions for new regulatory frameworks (safety, environmental, energy, water, ...), urban planning and infrastructural changes.

The speed of change in automotive can be enormous. For instance, 5 years ago there was no charge station in the Netherlands, and no electric car driving. Now, there are 5,000 thousand of (fast) charging points. Mid 2013, 10,000 (hybrid) electric vehicles were on the road, next year that will be more than doubled. In 2020, 200,000 charge points are planned (EC). We foresee a speed-up in 10 years’ time from the fuel cell cars.

Projections for the future of fuel cell cars, their costs and especially the lifetime of the fuel cells become more robust. Penetration is estimated between 5% and 50% of the personal car park in EU29 in 2050 [34]. Early April, the first commercial car (Hyundai ix35) was introduced in the Netherlands. Learning curves of hydrogen generation and fuel cell technology put confidence in a steady decrease of total cost of ownership, levelling the fuel cell electric car with other engine configurations from 2030 onward. [34]

A hydrogen-based economy requires a combination of technological breakthroughs, market acceptance, and large investments in a hydrogen energy infrastructure. The economic gap for introduction of fuel-cell based electric vehicles, is estimated at 100 billion Euro up to 2030 according to [34]. Combining the emerging hydrogen fuel cell cars might reduce overall introduction costs and/or increase the revenues of the hydrogen infrastructure. It may also limit or reduce investments in power infrastructure, as generation capacity is embedded in the cars. In the wake of this introduction, the position stakeholders will change drastically, forcing them to innovate in technology and in business models.

The value of electric vehicles on balancing an (increasingly intermittent) power grid can be significant and could amount to several billions of euros [35]. This applies to battery powered electric vehicles (charging when power supply is available) as well as hydrogen cars (using stored hydrogen to produce power when supply is short. [34]

One can imagine that success would not happen overnight, or even over years, but rather over decades. One can also imagine that would be a long-term process that would phase hydrogen in as the technologies and their markets are ready. Environmental and regulatory drivers such as EU directives on low-emission and zero-emission requirements will create near-term opportunities. The transport sector is key in the transition to a hydrogen-based low-emission economy.

If the introduction of electric non-fossil fuel cars is hampered, the climate policy of the EU and the Netherlands are in danger, or will incur higher societal and mitigation costs. The introduction of fuel cell cars needs a fine maze of fuelling opportunities to car owners. Otherwise, the fuelling inconvenience may become a show-stopper for early adaptors.

2. Utilisation plan

For utilisation purposes, a demonstration project is being set up to develop technology and physical integrations, which will serve as a test ground for this research (and vice versa). The commercialisation will be achieved in five steps:

- Subsystems developing and testing (The Green Village) / Component testing (2014-2015)
- Installation CaPP system in The Green Village, typically 5-10 cars, 0.5 MW power, heat / water (2016)
- Evaluation / Consolidation Concurrent with end date of CaPP project (2017)
- Pilot of CaPP system (50 cars, 5 MW peak power) (2018).
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These commercialisation steps are taken in an open innovation structure facilitated in The Green Village
Future Lab Car as Power Plant.

The user committee companies participated in a symposium on June 25, 2013, setting the scope and
development questions of the Car as Power Plant. See http://collegerama.tudelft.nl/Mediasite/Catalog-
/Full/ef0630926f184be3a63014249aab80d321 for full recordings of the presentations. Key players in the
power, gas and transport sectors have shared their vision and interest in this concept and elucidated how
the concept fits within their strategic challenges and business opportunities. According to David Green
(Shell) the future of energy in transport will be a mosaic of technologies, in which hydrogen plays a role.
Gerard Martinus (GasTerra) sees natural gas in mobility coming up, with natural gas being either on-
board or off-board reformed into hydrogen. Guy Konings (Stedin) stated that hydrogen mobility has a big
potential, and offers increased control for power grid operators. Finally, Nils Beers (BAM’s manager for
electric transport) stressed the speed at which personal mobility is changing.

The symposium concluded there is great potential for the concept. Six type of challenges should be
addressed: technical, economic, consumer perception and incentives, co-operation, and regulation. They
identified a first set of (market) opportunities for the parking industry, utilities, the car industry, and car
owners. Issues to be addressed: Strategic issues, use spectrum of fuel cells in cars, develop payment
models. Start with one car for engineering and then purchase a fleet of FCEV’s for testing, learning. Most
important: Build a business case, based on the consumer’ interest.

The partners involved are the companies mentioned in section 4. The network of industry involved is
more extensive, with car service, garage and gas stations (Bovag, RAI), gas and hydrogen suppliers
such as Linde Gas, equipment suppliers such as HyGear and Hyet, but also social enterprise companies
(Kirkman Company), governments and environmental organisations. Social media based mobility
provider Seatz, and Netherlands’ publisher of the leading (on-line) car magazine Sanoma Media
(Autoweek) also got involved.

Recently, several global car manufacturers (Hyundai) showed interest in the Car as Power Plant concept.

The participation in the User Committee is confirmed by emails or letters of support by the following
organizations:

· GasTerra (International natural gas trading company; contact person: Gerard Martinus, Energy
  transition manager, Stationsweg 1, 9726 AC Groningen, 0683524318,
  Gerard.Martinus@gasterra.nl)

· Shell Global Solutions International (Energy Company, Gert Jan Kramer, Manager Future Energy,
  Grasweg 1, 1031 HW Amsterdam, 0655123165, Gertjan.kramer@shell.com)

· Eneco (Power company; contact person: Glenn Bijvoets, Energy transition manager, Marten
  Meesweg 5, 3068 AV, Rotterdam, 061 10 34834, glenn.bijvoets@eneco.com)

· Stedin (Energy infrastructure company; contact person: Guy Konings, Blaak 8, 3011 TA,
  Rotterdam, (0)65 37 46236, guy.konings@stedin.net)

· BAM (Construction Company, contact person: Nils Beers, business development manager electric
  transport, Plantijnweg 22, 4104 BB, Culemborg, (0) 63 16 33669, n.beers@bam-it.nl)

· Q-Park (car park operator; contact person: H. Pot / Mark van Haasteren, Stationsplein 12-E,
  6221 BT Maastricht, 030 60 42149, hpot@vpdj.nl)

· HyTruck (hydrogen fuel-cell powered vehicles, contact person: Eric Beers, Flevoland 1, 1948 RH
  Beverwijk, 025 12 75015, Eric.beers@b-m-l.nl)
3. **Intellectual property, contracts and patents**

The researchers will publish their results and findings in professional, business and general public magazines, newspapers and websites. In the Green Village the car as power plant concept will be tested, demonstrated and showed. Via tours, courses, workshops and conferences organised by the Green Village the results will be discussed and presented to a broad public.

To our knowledge, there are no patents which may block the planned research and utilization.

7d **Positioning of the project proposal**

Dealing with the challenges of the future power system requires an interdisciplinary approach: integrating knowledge from electrical engineering, mathematics, computer science and policy analysis. That is why the Delft University of Technology started the **Power Web** initiative [http://powerweb.tudelft.nl/](http://powerweb.tudelft.nl/), where three faculties cooperate in joint research to provide the society with fundamental tools to make the existing power system intelligent and robust.

The Delft Center for Systems and Control has a unique profile in the way it combines model predictive control and multi-agent model predictive control of large-scale infrastructure and transportation networks. DCSC cooperates with ETH Zurich (Morari, Andersson), University of Seville (Camacho), University of Lund (Rantzer), Politecnico di Milano (Scattolini), University of Wisconsin-Madison (Rawlings).

The Energy & Industry Section focuses on the development of structured methods and tools for integrated design and management of process systems in the industry and the energy sectors. E&I cooperates with Politecnico di Torino (Bompard), Katholieke Universiteit Leuven (Deconinck), Carnegie Mellon University (Ilic) and the Institute for Energy of the Joint Research Centre European Commission.

The Applied Physics Department and the Green Village (100% subsidiary of TUD) works with research groups from the Erasmus University, University of Leiden, Masdar University, and various University of Applied Science (a.o. Hanze Hogeschool), and the Innovation and Energy Transition groups of various industries. The Car as Power Plant forms one of three pivotal Future Lab programmes of the Green Village, embedded in the Delft Energy Initiative. In the field of energy, faculties of the TU Delft work closely together under the umbrella of the ‘Delft Energy Initiative’ [www.tudelft.nl/en/research/energy/](http://www.tudelft.nl/en/research/energy/), representing about 700 energy researchers.

The E&R group of Utrecht University has regular research cooperation with a.o. ETH Zürich, Lawrence Berkeley National Laboratory/UC Berkeley and Lund University that all have carried out research in areas related to this research proposal.

8 **Description of the proposed plan of work**

The 4-years workflow in each project consists of a number of tasks (T) and the yearly deliverables (D).
Subproject PhD1. Design, assess and analyse the fuel cell car as power plant (CaPP) in integrated transport and energy systems

Year 1:
T1.1. Research Initiation
- Literature review
- Data collections review (on existing model based designs)
- Resource analysis
- User committee inputs
D1.1. Paper on data sources and model resources relevant to the CaPP

T1.2. Data collection, learning curves and technology assessment
- desk research
- first Cycle Tempo model building
- interviews
- global detailed statistics

Year 2
T2.1. Conceptual framework building
- definition of building blocks
- interaction between building blocks
- study on exergy versus energy analysis
D2.1 Paper on integral energy system design, integrating heat, power and transport. Two conference papers.

T2.2. Model building
- Cycle Tempo (for gas, heat flows)
- Building MATLAB, SIMULINC (for power flows (Low Voltage)),
- Power grid (Medium Voltage and High Voltage), Natural Gas grids
- Transport models
D2.2. Computer model based design of integrated integral energy system. Paper on energy potential and bottlenecks in the CaPP system. Paper on energy and mass flows in integral system. One journal paper, two conference papers.

Year 3
T3.1. Interfacing the models for integral scenario analysis
D3.1. Computer tool / software package integrating simulation tools on the electricity system, the fuel system and the transportation system.

T3.2. Scenario (global) building,
- selection
- application
- testing / validation
- running, exploration
D3.2. Paper on scenario build-up and integration of existing scenarios. Paper on scenario possibilities and energy and exergy profiles.

Year 4
T4.1 Synthesis and final reporting
T4.2 Writing of the PhD thesis

Subproject PhD 2: Robust control of CaPP-based smart energy systems

Year 1:
T1.1 Problem formulation and literature survey
T1.2 Development of stochastic dynamic models for consumption and production profiles for individual households and consumers
T1.3 Development of hybrid models for fuel cell vehicles and other smart grid components
D1: Integrated hybrid model for a CaPP-based smart grid network (+ 2 conference papers)

Year 2:
T2.1 Development of an efficient hybrid MPC approach for a small-scale CaPP-based smart grid (5-10 vehicles)
T2.2 Development of a robust hybrid MPC approach for a small-scale CaPP-based smart grid
T2.3 Analysis and assessment via small-scale cases studies
D2: Efficient robust control approach for a small-scale CaPP system (+ 1 journal paper and 2 conference papers)

Year 3:
T3.1 Development of a robust hybrid MPC approach for a medium-scale CaPP-based smart grid (up to 50 cars)
T3.2 Development of a scalable robust hybrid MPC approach for a CaPP-based smart grid (with up to 500 cars)
T3.3 Analysis and assessment via medium to large-scale cases studies
D3: Computationally efficient and scalable robust control approach for medium and large-scale CaPP systems (+ 1-2 journal papers and 2 conference papers)

Year 4:
T4.1 Further improvement of the computational efficiency and robustness
T4.2 Writing of the PhD thesis
D4: PhD thesis (+ 1 journal paper)

Subproject PhD 3: Exploring effective incentive and organizational structures for the emergence of a CaPP system

Year 1:
T1.1 Problem formulation and actor identification
T1.2 System identification and decomposition
T1.3 Concept formalisation
D1: The concepts identified in T1.1 – T1.3 will be formalized in a formal ontology (+ 2 conference papers)
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Year 2:
T2.1 Per decomposed system/agent, determine the proper modelling methodologies
T2.2 Per model, formalisation and detailing properties per system/agent(group)
T2.3 Implementation in simulation program
T2.4 Model and data verification
D2: Design and development of a simulation environment for the CaPP system (+ 1 journal paper and 2 conference papers)

Year 3:
T3.1 Experimentation and sensitivity analyses
T3.2 Data analysis
T3.3 Model and data Validation
D3.1: Validated and verified model of a CaPP as a socio-technical system.
T3.4 Research on fundamental issues of complex simulation models:
  • Stability
  • Sensitivity
  • Robustness
  • Reliability
  • Predictability
D3.2: Report on the proper working and application of the model and methodology.
T3.5 Experiments with incentive, business models, client propositions to test scenarios for different selected case studies
D3.3: Report on experimentation
D3.4: 1-2 journal papers and 2 conference papers

Year 4:
T 4.1 Writing the PhD Thesis
D4: PhD Thesis (+ 1 journal paper)

Post-doc integrating project: Business models for CaPP
This sub-project will be performed part-time (0,5 fte) in the last three years of the project

Year 2
T2.1 Development of business models and strategies of the actors involved.
T2.2 Exploration of potential (future) strategic fits with the current business models of the relevant actors and barriers, if any, when implementing in practice. User committee involvement.
D2.1: definition and evaluation of the most promising business models from the perspective of different stakeholders

Year 3
T3.1 Comparison of the business models
D3.1 Feasibility assessment of the business models (+ 2 conference publications)

Year 4
T4.1 Analysis of strategic fit with the current business models of the relevant actors and barriers, if any, when implementing in practice.
T4.2 Investigation socio-psychological theories (a.o. "Theory of Planned Behaviour") to examine to what extent the behaviour of customers, involving not only the economic but also social and ecological aspects play a role in the accepting and usage of the CaPP technology.

D4.1 Final report (+ 1 journal paper)

9 Expected Use of Instrumentation

The PhD researchers and a post-doc will need a computer with existing software packages. These packages will be free of use for student applications. Some budget is needed for training on these models. The computers are from the existing inventory of TU Delft.

10 Scientific output and deliverables

Scientific output
Please indicate the scientific output resulting from this project. You can tick one or more boxes.

<table>
<thead>
<tr>
<th>Output</th>
<th>Number</th>
<th>Expected year of publication</th>
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<tbody>
<tr>
<td>Articles in refereed journals</td>
<td>11</td>
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<td>Articles in non-refereed journals</td>
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<tr>
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<td>Conference papers</td>
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<tr>
<td>Professional publications</td>
<td>See below</td>
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<tr>
<td>Other scientific output</td>
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Deliverables
Please indicate the non-scientific (e.g. cultural, social, policy-related, technological or economic) output in the table below. You can tick one or more boxes. You can add other deliverables, resulting from the project, to the list.

<table>
<thead>
<tr>
<th>Deliverables</th>
<th>Number</th>
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<tr>
<td>Professional publications</td>
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<tr>
<td>Publications aimed at general public</td>
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<td>Other deliverables (Workshops)</td>
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<tr>
<td>Other deliverables (Social media)</td>
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<tr>
<td>Other deliverables (Columns, interviews, TEDx, TV shows, etc.)</td>
<td>16</td>
<td>2014-2017</td>
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11 Literature
Give maximum 35 references of publications cited in the proposal.

1. The concept "Electric cars powered by fuel cells" was ranked first in the recent Forecast 2013-2025 of the World Future Society [http://www.wfs.org/next25/]
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Social Sciences
Physical Sciences
STW


Funds required

12 Budget
See explanatory notes at the end of this form

Summary of project budget
Complete the table below.
* In case of co-funding of personnel or material costs it must be made clear whether it concerns in-cash or in-kind co-funding by placing an X in one of these boxes.

<table>
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<th>To be funded by NWO (Component A)</th>
<th>Co-funding (Component B)</th>
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<td>Description</td>
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<td><strong>Total budget</strong></td>
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<td>€ 744.243</td>
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</table>

or in-kind co-funding by placing an X in one of these boxes.

**Statement by the applicant**

I have completed this form truthfully

Name: Zofia Lukszo

Place: Delft

Date: 24 September 2013

Please submit the application to NWO in electronic form (**PDF format is required**) using the Iris system, which can be accessed via the NWO website (iris.nwo.nl). For any technical questions regarding submission, please contact the Iris helpdesk (iris@nwo.nl). The electronic form must be submitted before 24 September 2013, 14.00 hours.
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Social Sciences
Physical Sciences
STW