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The ENERGY ECS Project: Smart and Secure Energy Solutions for Future Mobility

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

Romani A., Crescentini M., Rusu C., Staaf H., Ambrosio M., Chiaberge M., et al. (2023). The ENERGY ECS Project: Smart and Secure Energy Solutions for Future Mobility. Institute of Electrical and Electronics Engineers Inc. [10.23919/AEITAUTOMOTIVE58986.2023.10217190].

Availability:

This version is available at: <https://hdl.handle.net/11585/950585.2> since: 2023-12-13

Published:

DOI: <http://doi.org/10.23919/AEITAUTOMOTIVE58986.2023.10217190>

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(Article begins on next page)

This is the final peer-reviewed accepted manuscript of:

A. Romani *et al.*, "The ENERGY ECS Project: Smart and Secure Energy Solutions for Future Mobility," 2023 AEIT International Conference on Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE), Modena, Italy, 2023, pp. 1-6,

The final published version is available online at:

<https://doi.org/10.23919/AEITAUTOMOTIVE58986.2023.10217190>

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The ENERGY ECS Project: Smart and Secure Energy Solutions for Future Mobility

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Abstract—Electric and smart mobility are key enablers for their green energy transition. However, the electrification of vehicles poses several challenges, from the development of power components to the organization of the electric grid system. Moreover, it is expected that the smartification of mobility via sensors and novel transport paradigms will play an essential role in the reduction of the consumed energy. In response to these challenges and expectations, the ENERGY ECS project is pursuing smart and secure energy solutions for the mobility of the future, by developing power components, battery charging electronics, and self-powered sensors for condition monitoring, along with advanced techniques for grid management, applications of artificial intelligence, machine learning and immersing technologies. This paper presents the project's objectives and reports intermediate results from the perspective of the targeted use cases.

Keywords—energy, mobility, electronics, components, systems, sensors, batteries, drones, grids

I. INTRODUCTION

The Energy ECS project [1] is a 3-year European project targeting the development of smart and secure energy solutions for future mobility. Mobility is dealt with at different levels and within several applications. As a general objective, the project aims to develop a set of technologies related to Electronics, Components and Systems (ECS) to improve the digitalization of e-mobility systems and related energy solutions. Most of all, the project aims to generate valuable know-how and business opportunities in Europe. The approach is based on manufacturing capabilities, combining hardware, software services and data. The benchmark reference for the technologies are relevant use cases proposed by the industry partners, with associated specifications. The project involves a series of industry-relevant use cases representing a series of aspects related to future mobility and the associated energy challenges.

The first challenge (Use Case 1, UC1) consists of the development of autonomous drone ecosystems, capable of interactions with transportation systems, autonomous control, and improved resilience. Drones may take advantage of circulating e-buses, equipped with charging electronics on their rooftops and transportable PV-based charging stations, to improve their range and provide novel applications to this sector of transportations. Research in the project involves

aspects related to flight control, charging electronics, photovoltaic conversion, battery reliability, and compatibility with European regulations.

Another sector that is expected to take advantage from ECS is intramodal transport by smart containers (Use Case 2, UC2). Enabling smart sensing functionalities and efficient use of energy in the hardware will enforce advanced monitoring capabilities, cargo locations, and fleet management. PV technologies are adopted for charging batteries of wireless sensors. Smart wireless communications using novel materials and substrates complement the application.

The advent of electric vehicles (EVs) introduces new challenges for the electric grid, like the balancing and AI-based monitoring of microgrids specifically in connection of charging/discharging of EVs (Use Case 3, UC3). The goal is to improve grid resilience and reliability, and to enable renewable energy integration by using power quality systems, smart grids and battery energy storage.

EVs and their charging, due to the impact on electric grids, play a central role in the mobility and energy related transformations. In this context the project targets vehicle-to-grid technologies by studying bidirectional onboard and offboard chargers for EVs (Use Case 4, UC4).

Another aspect of smart mobility targeted by the project is the development of self-powered sensing systems in tires (Use Case 5, UC5) to improve safety and optimize energy usage. Currently, most commercial solutions are battery-powered. UC5 aims at developing kinetic and strain energy harvesters as alternative or additional power sources. In this context, novel, flexible, eco-compatible energy harvesters, and their power electronics are among the expected outcomes.

Autonomous driving represents one of the ultimate challenges in smart mobility. As a potential application, EVs or e-buses may autonomously drive to charging station at a bus depot area, including real time location, safe approaching and charging (Use Case 6, UC6).

It is also worth to mention that highly optimized trustworthy artificial intelligence (AI) is an important part in Energy ECS, that aims at optimizing the pre-trained models for target hardware available in several Use Cases (UCs). An efficient training start from high quality data and provides



Fig. 1. Experimental tests of drone landing on mobile platforms.

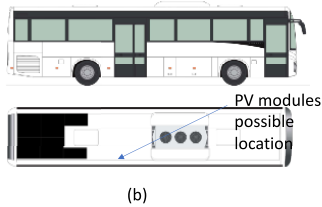
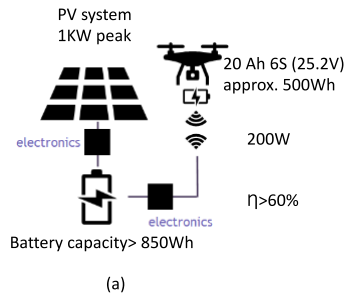


Fig. 2. Monitoring (a) Representation of the main specifications of the PV module, (b) Possible location of PV module on the UC1 bus

better generalization, whereas bias and variances in data negatively affect training and inference. Since vulnerabilities of AI systems can incentivize cyber attacks, it is vitally important to have trustworthy AI according to EU draft AI act and US executive order. AI risk and trustworthiness are related to technical characteristics (accuracy, reliability, robustness, resilience, or security), socio-technical characteristics (explainability, interpretability, managing bias, privacy, safety, loyal), and follow guiding principles such as fairness, accountability, transparency. In Energy ECS, different UCs are using AI guiding principles for their AI systems.

This paper showcases a selection of multidisciplinary research activities carried out by the Energy ECS project. The objectives, challenges, and adopted strategies will be presented and described with respect to the current state of the art. The next sections will describe a selection of the research activities performed within the project use cases by focusing on the adopted methodologies and expected impact.

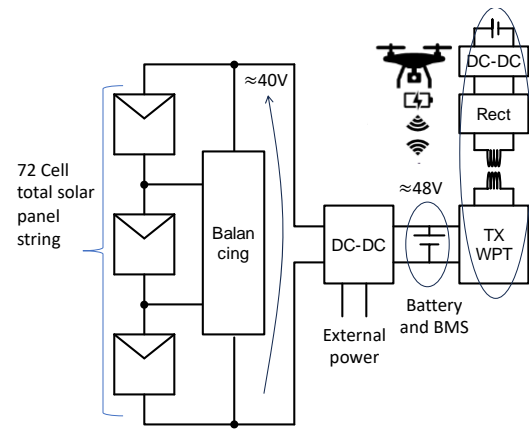


Fig. 3. Representation of the basic structure to be adopted for the Power management system.

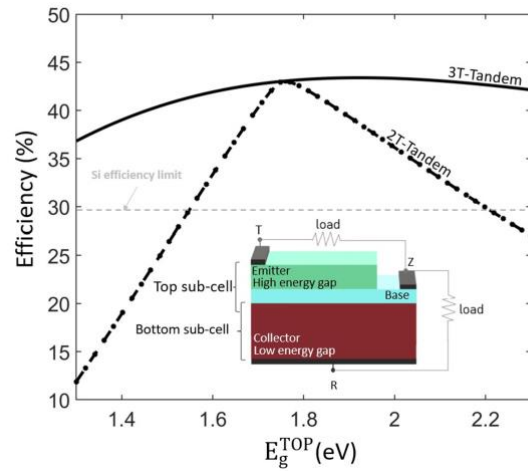


Fig. 4. Limiting efficiency of 2T and 3T silicon based tandem solar cell. The inset shows the bipolar transistor architecture of the 3T tandem.

II. USE CASE 1: MONITORING, CONTROL, AND ENERGY MANAGEMENT FOR DRONE ECOSYSTEMS

Unmanned Aerial Vehicles (UAVs) are highly versatile vehicles that can be employed to accomplish a wide variety of tasks in a fast and efficient manner. The main drawback of UAVs is the short-range autonomy due to the limited battery capacity. Thus, in a vision of a smart and connected city, docking stations providing charge from renewable energy could be deployed on the roofs of public transports.

Landing on docking stations requires a localization precision higher than the one usually provided by GNSS receivers, especially in harsh conditions like urban canyons. Thus, Ultra-Wide Band (UWB) technology is employed to provide a reliable localization due to its high ranging precision, obstacle penetration capabilities and robustness against interference. Positioning is achieved through a least squares multilateration algorithm, which takes as input the distances given by the UWB devices and returns the relative position of the two systems in the rover reference frame. This information is very noisy and needs to be rotated in the drone reference frame for control purposes. Therefore, it is then fused with UAV sensors and UGV compass data in a loosely coupled Kalman filter, allowing up to 5 cm accuracy when the drone is within 1 m from the rover. The filtered relative position estimate is then passed to a gain scheduling PID speed controller, which ensures fast tracking and acceptable overshoot in both chase and landing phases. The first step is

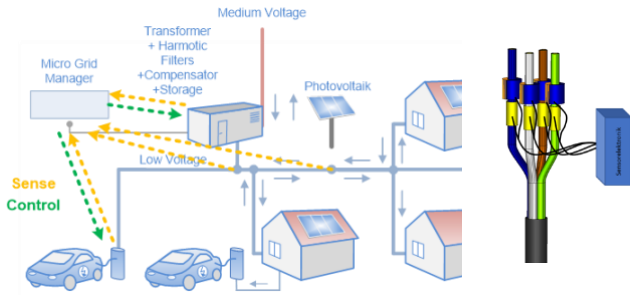


Fig. 5. Monitoring points in the electrical distribution grid (left) and sensor module attached to a cable with harvester/current sensor and phase detector (right).

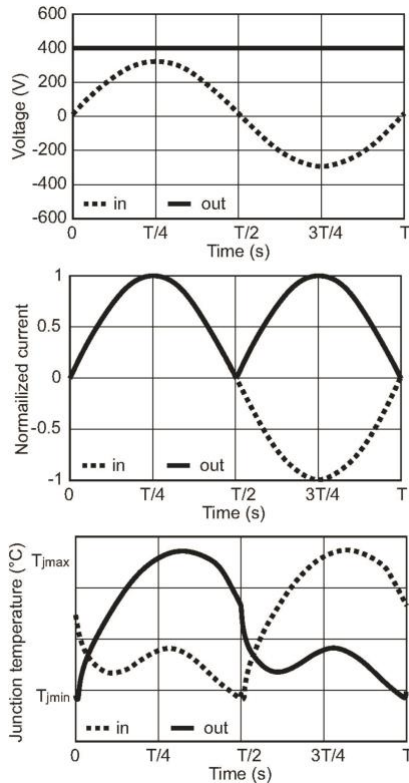


Fig. 6. Simulated envelope of the input (dotted) and output (solid) waveforms of the transistor in the Bridgeless Totem Pole AC-DC conversion circuit with 230 Vrms, 50 Hz sinusoidal input, and 400 V DC output voltage. The time scale is parametrized by the period T of the AC input signals.

handled by a proportional control algorithm, while the second by a proportional-integrative-derivative one. Since the main problem of the proposed landing system is the misalignment between drone and rover compasses, this control algorithm is robust with respect to orientation errors, allowing successful landings with errors up to 40° (Fig. 1).

Lithium-ion batteries have high-energy density and no memory effects [2], but they do present numerous degradation mechanisms affecting lifetime [3]. Therefore, accurate real-time monitoring of battery state is a crucial aspect in UC1. Commercial state-of-charge estimation algorithms are based on either Coulomb counting or voltage methods [4], both suffering from severe time drifting errors. Energy ECS studies the application of electrochemical impedance spectroscopy (EIS) techniques for the in-situ and in-operando monitoring of battery state parameters that can overcome the limitations of current methods. Energy ECS aims at overcoming the cumbersome instrumentation and long measurement times

required by EIS, by proposing multi-sine sigma-delta modulated excitation to shorten measurement time and gather the whole spectrum in a single time frame [5] and by developing a miniaturized EIS measurement system to sense single battery cells [6][7]. Sigma-delta modulation applied to the excitation signal allows to use low-complexity 1-bit digital-to-analog converters and improves the signal-to-noise ratio by shaping the quantization noise out of the band of interest.

Power management in drones landing on e-bus rooftops addresses two main challenges: effective energy extraction from a moving system subject to shading and an efficient and light wireless charging system. Fig. 2(a) provides a concise description of the photovoltaic and power management system and (b) possible location of PV module. The overall energy required for the drones can be determined by combining the battery capacity and the battery charging voltage (approximately 500Wh). Considering a recommended minimum wireless charging efficiency of 60% in the worst-case scenario, the PV battery capacity needs to be at least 850Wh to fully support the charging of a single drone.

In order to minimize currents, a battery voltage of 48V has been chosen. The power management architecture is configured as reported in Fig.3, where the balancing system allows to raise the conversion power up to 50% in shading conditions and improves the stability of the maximum power extraction point. The DC-DC converter control implements MPPT and controls battery charge. The wireless charging system is based on an inverter on the transmission section and a rectifier on the receiver followed by a DC-DC converter. The coils have been designed to minimize losses and weight of the structure. An important feature is the estimation of the type of losses (conduction, eddy current and core) and their location (TX/RX winding or TX/RX core) [8]. Also, to reduce the size and weight inside the drone, a particular three-level structure DC-DC converter has been developed to minimize the value of the inductances for the battery charge [9].

Integration of PV modules on bus rooftops requires to maximize the nominal cell efficiency, due to the limited available area, and also the actual energy yield regardless of module self-heating and fluctuations of the incoming solar irradiation [10]. Tandem solar cells, made by a high bandgap cell on top of a lower gap one, achieve significantly higher efficiency than single gap ones reducing thermalization losses, therefore being less prone to self-heating. Moreover, the adoption of a three-terminal (3T) architecture, with independent loads connected to the two sub-cells, instead of the conventional 2-terminal (2T) one ensures the highest energy yield [11]. As seen in Fig. 4, for optimal material choice and in standard test conditions, the two tandem architectures achieve the same nominal efficiency. On the other hand, under on-field conditions, the 3T one generates higher power. IUNET-POLITO has studied monolithic 3-T tandem cells taking advantage of the bipolar junction transistor (Fig. 4, inset) structure [12]. In this approach, two sub-cells with inverted polarity are seamlessly connected through their own layers with same doping polarity, forming the so-called base of the transistor. The cells act as two counter-series diodes that, under photovoltaic operation, work independently, maximizing the attainable efficiency. An interdigitated layout of the emitter and base current collecting grids is used. Proof-of-concept designs for perovskite/silicon 3T tandems were developed based on transport, optical, and circuit simulations.

TABLE I. SIMULATED PERFORMANCE OF A BRIDGELESS TOTEM POLE AC-DC CONVERSION CIRCUIT WITH 230 VRMS, 50 HZ SINUSOIDAL INPUT, 200 KHZ SWITCHING FREQUENCY AND 400 V DC OUTPUT VOLTAGE. THE HEATSINK THERMAL RESISTANCE IS ASSUMED TO BE 0.5 °C/W.

Transistor part	$R_{DS,on}$ (m Ω)	I_{MAX} (A)	# parallel transistors	Power rating (kW)	Transistor losses (cond.+switch.) (W)	Max junction temperature (°C)	System efficiency (%)
GS66508B	50	30	1	2	15.64	47	98.15
GS-065-030-2-L	50	30	1	2	14.55	46	98.57
GS-065-030-2-L	50	30	2	4	33.27	81	97.58
GS-065-060-X	25	60	4	5	76.10	135	95.88
GS-065-150-1-D2	10	150	1	4	108.14	141	95.06

III. USE CASE 2: SMART SENSORS FOR INTERMODAL TRANSPORT

For intermodal transport (primarily sea, rail and road) 95% of the world's dry containers are not sensorised. For economical, compliance and environmental reasons many stakeholders are interested in what kind of journey the container and its contents has had in terms of location (to minimize transportation time and maximize energy efficiency), temperature, humidity, vibrations, shock, etc. To this end, Energy ECS is developing a set of technology platforms for incorporation into a retrofittable WSN (wireless sensor network) asset tracking device (IoTPASS) provided by Irish SME partner NetFeasa. This includes PV panels from partner CSEM, a discrete power management solution from RISE, an energy harvesting power management IC (PMIC) & a battery life/energy harvesting simulation model from Tyndall. A major impediment to retrofitting such devices is battery life. A key message here is that significant battery life extension from 2 years to >10 years, and in some cases full autonomy is possible through collaborative design and integration of platforms both reducing the power consumption and maximizing the energy harvested.

In this context, Energy ECS investigates the use of UWB antennas to receive or transmit the necessary information for the system [13], under strict dimensional and performance constraints, and in presence of metal walls. To this aim, circular polarization antennas overcome pointing and orientation issues. Moreover, it is necessary to integrate devices adopting different protocols over multiple frequency bands. In the context of multiple coexisting communications, adopting one antenna for each standard results in increased area, complexity and cost, and is prone to interferences. To overcome these issues, the adoption of a wideband antenna allows to share it for the different types of communications, while reducing the overall volume, and where interference problems are minimized. In the Energy ECS project, an ultra-wideband cavity-backed spiral antenna with absorbing material is planned [14], which covers frequencies ranging from 0.7 GHz to 2.2 GHz, in order to accommodate numerous 3GPP bands. Its dimensions must allow its placement inside the cavity of a metal container wall, ensuring optimal functioning, circular polarization, robustness, and high radiation efficiency.

IV. USE CASE 3: MONITORING OF DISTRIBUTION GRID FOR WIDE-RANGE E-MOBILITY CHARGING INFRASTRUCTURE

Energy ECS [1] also carries out the development and realization of suitable components for condition monitoring of electrical distribution grids. By means of suitable sensor systems, communication and IT infrastructure components,

relevant information on network infrastructure elements at neuralgic points is collected, aggregated, and communicated (Fig. 5) [15]. This information can be used directly for a highly dynamic grid-serving control of grid components to ensure a robust and efficient use of the distribution grid also for the wide-range charging of EVs. The main objective is the development and realization of energy-autonomous sensor systems for recording the status of relevant components of the distribution network. The work to be carried out includes sensor principles as well as the field of energy harvesting or the field of sensor signal processing [16].

Critical points in the distribution network were identified in discussions with distribution grid operators. Overloads can occur due to increased power draw, e.g., by EV charging, and due to decentralized feed-in by renewable sources, photovoltaic power favoured by weather conditions. The two most important spots are transformer stations and distribution cabinets, which are used in urban areas to distribute electrical power to the streets. The main parameters to be measured are current and phase between voltage and current in each conductor. Further values can be derived from these basic parameters by calculation and signal processing. The concept for the sensor systems uses inductive energy harvesting and avoids so contacts to the three phases. According to the developed concept, the outgoing conductors will be equipped with energy-autonomous wireless sensor systems primarily for current and phase measurements. Fig. 5 shows the principle with an energy harvester and current measurement with a phase detector for each wire. The data is transmitted via LoRaWAN radio interface to the microgrid controller and from there to the network operator's control center.

V. USE CASE 4: GAN-BASED ON BOARD CHARGERS

IUNET-POLITO made a feasibility study on the application of Gallium Nitride (GaN) transistors in the design of on-board chargers (OBCs). The OBC requirements in terms of efficiency, power handling and size (that strongly affects the design of the cooling systems) are above the current state of the art of commercial products and literature solutions [17][18]. Looking at AC/DC conversion, GaN devices are more promising than Si-MOSFETs in implementing OBCs based on bridgeless totem-pole configurations [19]. Their zero reverse recovery charge allows to increase the switching frequency up to the MHz thus reducing the circuit size, however at the price of a more complex control and a higher component count to implement soft switching. The capabilities of several GaN packaged devices have been evaluated when embedded in Bridgeless Totem Pole AC-DC circuits, based on simulations carried out using the manufacturer electrical and thermal models [20]. The performance of the circuit is estimated under different

conditions, i.e., different power ratings and adopted GaN transistors, assuming constant switching frequency of 200 kHz and 400 V output DC voltage and room temperature operation (25°C). The device input and output current waveforms and their junction temperature, normalized with respect to their maximum, are reported in Fig. 6.

In fact, current and temperature maximum values, summarized in Table I, depend on the explored transistor and configuration, while the waveform shape is the same. In Fig. 6 the input and output voltage across the devices are shown too. Table I highlights that higher power handling requires either the adoption of transistors with high current rating or paralleling several devices. In either case, the junction temperature increases with the overall power with a consequent system efficiency reduction. In case a single high-current transistor such as the GS-065-150-1-D2 is used, the efficiency drop can be ascribed to the switching losses which, despite the decrease of conduction losses induced by on-resistance reduction, are very high. Conversely, paralleling more transistors with lower current rating but higher $R_{DS,on}$ features lower switching losses, but higher conduction losses. However, none of the analysed transistors allows for 22kW power with maximum temperature below 150°C, as required by this project. In fact, the challenging requirements of this project call for ad hoc studies of appropriate PFC (as well as DC-DC converter) topologies able to provide the required output voltage levels and power handling, while respecting the safe operating operation of the active devices. The heat sink design is then another critical aspect to consider. Despite that, GaN transistors show great potential in this application.

VI. USE CASE 5: SELF-POWERED TIRE SENSORS

Smart transportation systems require a significant amount of hardware for sensing, data processing and communications. The push towards electrification and autonomous driving is giving sensing and electronic systems a huge role. A notable example of wireless battery-powered sensors are tire pressure monitoring systems. Energy ECS is investigating novel solutions for low-cost, lead-free kinetic and strain energy harvesters, design of micropower conversion and management electronics, study of new materials for smart interconnections of system parts.

Energy harvesting is obtaining growing interest in automotive applications, e.g. with RF power transfer [21] and mechanical energy [22]. Concerning tires, several electromechanical energy harvesters have been considered in literature on different areas of tire assemblies [23]. The maximum reported values of extracted power for PZT-based harvesters are in the order of mW. However, these assemblies [24] are often complex, rigid, and PZT is brittle and subject to wearing. PVDF is a piezoelectric polymer that has lower performance than PZT but allows for flexibility and larger deformations for tire application [25][26][27]. Triboelectric harvesters [28] are also under development within UC5. For test setups inside tires, specialized measurement electronics with wireless communications, e.g. Bluetooth and Wi-Fi, was developed. Fig. 7 reports a selection of measurements performed on tires at the premises of partner Nokian Tyres.

Reliability of the connectors working in a harsh environment was tested in a simulated environment at different duration and speed levels. A novel connection technology developed at AMAT and based on polyimide foil, low-temperature Ag pastes and electrically conductive

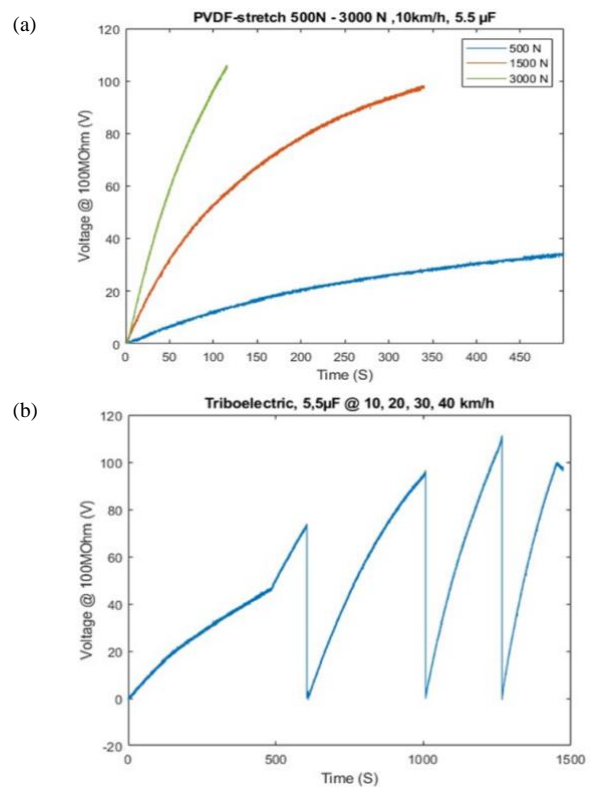


Fig. 7. Characterization of energy harvesters in tires: rectified voltages on a 5.5 μF capacitor from (a) PVDF piezoelectric for various tire pressures; (b) triboelectric at few tire velocities (RISE).

adhesives proved to be suitable in preliminary trials, maintaining a good mechanical contact after 20 hours at 100 km/h. Industrialization and scalability of such connection will need to be further investigated to determine its applicability.

To successfully exploit electromechanical harvesters in tires, IUNET-UNIBO is addressing several open challenges in the development of micropower management circuits. First, the piezoelectric voltages are in the order of several hundreds of V, and the relatively low associated electrical charge limits the power budget. An additional challenge consists in the minimization of leakage and quiescent currents. In fact, at voltages of hundreds of V, even the tiniest leakage current would waste significant power. Unfortunately, most commercial micropower converters have limited input voltages up to few V [29]. Moreover, to overcome the difficulty of performing MPPT with irregular motions at low operating frequencies, the so called synchronized-switch energy harvesting techniques [30] appear significant. Synchronous electric charge extraction [31] tracks vibrations by triggering the power converter exactly on voltage peaks. However, most solutions in literature are designed to work with voltages in the order of few tens of volts [32], which makes them not suitable for operating in the smart tire. IUNET-UNIBO has developed tiny high-voltage micropower management circuits and is working to port synchronized-switch converters to such high-voltage scenarios.

To complement the activity, DTT conducted a comprehensive analysis of the structural behaviour of a piezoelectric material, based on Finite Element Method (FEM). The analysis is performed on a piezoelectric material patch installed within a tire and aims at investigating how the geometry of the patch affects the harvested energy. FEM simulations assess the

performance and integrity of the design under real-world stresses and allow to optimize the transducer design and structural properties. The tire is divided into small elements and its structural response is analysed. Deformation and stress distribution are predicted while localized effects and non-linear behaviour are highlighted by considering the intricate structure and material properties of the tire. The integration of FEM simulation with empirical models like the Magic Formula tire model, improves predictions of the piezoelectric energy harvesting module behaviour. The adopted method involves partial differential equations (PDEs), with thirteen independent characteristics to be taken into account. Material properties are derived from datasheets [33] while stiffness and compliance matrices are computed using known properties like Young's modulus and Poisson's ratio.

ACKNOWLEDGMENT

This project has received funding from the ECSEL Joint Undertaking (JU) under grant agreement no. 101007247. The JU receives support from the European Union's Horizon 2020 research and innovation programme and Finland, Germany, Ireland, Sweden, Italy, Austria, Iceland, Switzerland.

The authors thank Biraj Harnal of Digital Twin Technologies, Sobhan Sepehri, Elof Köhler, Edoardo Trbaldo of Research Institutes of Sweden, Gianluca Dara, Matteo Cagnoni, Pietro Testa of Politecnico di Torino, Ruben Specogna, Sara Ceschia of University of Udine, and Giancarlo Pastor for their support to project activities.

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