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An overview of the concept and technology of ubiquitous energy

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HIGHLIGHTS

- Ubiquitous energy signifies an access to energy everywhere and any time.
- Definitions and criteria for ubiquitous energy technologies and systems.
- A systematic review of the latest innovations in energy generation, storage and distribution.
- Research and development should focus on the portability, scalability and integrability.

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ABSTRACT

The continuous and rapid development of energy technology challenges the scientific community to ponder the long-term energy evolution from the perspective of sustainable energy transition. We state that one of the key challenges for the new (post-fossil) energy era is to guarantee to all energy users an access to adequate resources of energy everywhere and at any moment of time. To crystallize the key ideas of such a pervasive energy supply chain into a single concept, we introduce the concept 'ubiquitous energy'. The main contribution of our paper is to create a discussion framework for the concept and to identify the most relevant technology pathways for the realization of 'ubiquitous energy'. Hence, we first present the background of the concept and discuss matters concerning the 'quality of energy to be present everywhere'. Secondly, we review the latest innovations in energy technology with respect to the energy supply chain and summarize technology pathways to 'ubiquitous energy'. To that end, we describe a systematic framework to classify energy technologies under energy generation, storage, transmission and distribution. We conclude that 'ubiquitous energy' covers various solutions in both scope and degree of integration, but the most prominent trend of development is the use of distributed and shared resources and local energy supply chains. Here, the research should focus on integrated and mobile energy conversion and storage options and wireless power transmission.

1. Introduction

The global energy consumption is predicted to rise by 28% by 2040 in comparison with the year 2017 [1]. The rise accompanies the economic growth. The increase of energy consumption is also fed by the rebound effect, which is the consumers' reaction to low energy costs due to improved energy efficiency and enhanced availability of energy [2]. Furthermore, the continuous evolution of the techno-economic system may cause unpredictable effects, partly due to increasing digitalization and automation (e.g. the energy demand of virtual currency mining [3]). By 2100, at latest, a plateau has been estimated to be reached, the energy consumption settling at the level of about 40% higher than in 2017 [4]. The growth is limited by both techno-economic constraints and the intention to improve the efficiency of the whole energy system. Ultimately, physical constraints such as overheating due to entropy generation prevent the energy consumption from growing without limits [5].

To fulfill the demand of clean energy indefinitely, the sustainable energy transition is expected to see the revolution of renewable energy and nuclear power, including nuclear fusion [6]. Particularly, the energy sector calls for innovations until 2050, which is the target year to approach carbon-neutrality in the European climate strategy [7]. However, when preparing for the post-carbon era, which can be also called 'new energy era' as opposed to 'fossil energy era', ensuring the accessibility to energy can be considered a challenge equal to the continuous quest of new energy sources. The requirements for the

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future energy system regarding the tolerance of disturbances such as extreme weather conditions will be unprecedented. Hence, there will be a pursuit of energy flexibility, resilience and minimal dependency on heavy and expensive energy infrastructures such as wired power grids and gas distribution networks [8]. Both distributed and centralized infrastructures within the whole energy supply chain will be required [9]. Moreover, the need to extend the energy supply chain in remote and inaccessible locations will strengthen in the future. For example, the planned space colonization call for 'space-resilient' structures (i.e. colonies and habitats), where both the materials and energy are supplied in terms of 'in-situ resource utilization' [10]. Correspondingly, micro- and nano-scale energy supply mechanisms for biomedical devices implanted in human body will be needed [11].

Based on the discussion above, we deduce that the transition to the new energy era particularly calls for research and development on such technologies and infrastructures that guarantee all the energy consumers an access to adequate resources of energy and power everywhere and at any moment of time. Due to the versatility of the technology domain and its rapid development, the knowledge on the related technologies is fragmented and the literature reviews are often too technology-specific. Thus, we identify a need to discuss the terminology, attributes and technologies with an aim to specifically facilitate finding sustainable pathways towards pervasive energy supply chains.

In this paper, we conceptualize the prevailing ideas of pervasive energy supply chains under the concise term 'ubiquitous energy'. We also propose a systematic, portfolio-based framework to identify and characterize the key energy technologies and critically review and analyze the literature with an aim to identify the technology pathways in the aforementioned context. The purpose of this review article is to provide systems researchers and engineers with a compact but extensive, analytically outlined framework of information and terminology, where the central developments and advances related to ubiquitous energy are readable in a single document.

2. The concept of ubiquitous energy

2.1. Conceptual background

The word 'ubiquitous' is derived from the Latin word 'ubique', which means 'everywhere'. In dictionaries, the word is interpreted as a quality (or ability) of existing, being present or appearing everywhere. Also the temporal dimension is included in the definition, for example, in the Merriam-Webster dictionary, which characterizes 'ubiquitous' as 'being everywhere in the same time'. Conventionally, the word has been used in computer sciences in terms of 'ubiquitous computing' [12]. In this context, the meaning of 'ubiquitous' usually extends from the quality of being present everywhere at the same time to the quality of being present everywhere at *any* time. The idea has been further elaborated in connection with 'ubiquitous community', which is interpreted as the human presence and activity in both physical and digital spaces, such as Social Medias [13]. Again, the use of the word has spread to numerous applications, including ubiquitous manufacturing [14], learning [15] and smart cities ('ubiquitous cities' or 'u-cities') [16]. Basically, the criteria of being 'ubiquitous' are somewhat specific for each field of application.

Interestingly, the term 'ubiquitous energy' as such was first used as such in a scientific paper by Könnölä et al., who named 'the existence of a well-developed and ubiquitous energy system' as a Techno-Institutional Complex (TIC), i.e. a barrier hindering the development of renewable and sustainable energy infrastructures with the level of services comparable to conventional power generation and distribution and liquid transportation fuel systems [17]. Even though conventional energy systems are well-developed and pervasive in the sense that an extended network of power grids, fuel stations and power plants exists, there are deficiencies. For example, the access to power in rural areas is limited and exposed to faults and blackouts. As well, the urban environments are prone to challenges, such as a scarcity of charging points for electric vehicles or mobile appliances.

In recent, energy-related publications, the word 'ubiquitous' has been commonly incorporated in energy management, information systems or energy services [18]. For example, when defining the concept of 'ubiquitous city' (u-city), Rad et al. name 'ubiquitous power' as one of the criteria of omnipresence [16]. Here, sub-criteria are assigned to 'ubiquitous power' to characterize the information management and system control in terms of appropriate interfaces and communications between the network and its components and users, a real-time control network and remote detection of operation. In the same context, the Ubiquitous Energy Network (UEN) has been introduced by Song et al. as a combination of information, energy and thing networks [19], which has been further elaborated by partly the same Chinese researchers under the term Ubiquitous Energy Internet [20]. The aforementioned concepts uphold the traditions of the 'ubiquitous computing', however, and they do not extend the meaning of the expression 'ubiquitous energy' into physical energy systems.

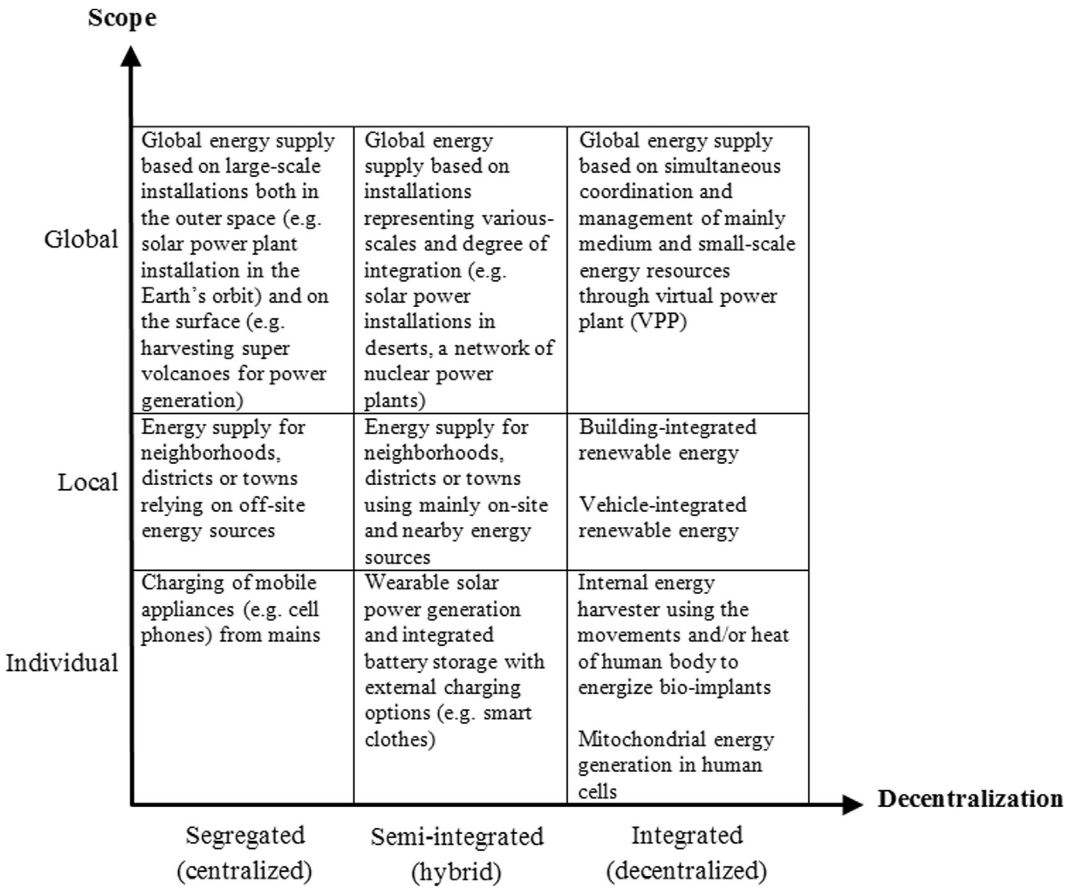
In other than academic contexts, 'ubiquitous energy' has been often associated with integrated renewable energy. It has been adopted, for example, to the name of the startup company 'Ubiquitous Energy Inc.', which develops transparent solar cell technology for mobile applications and smart windows. The word 'ubiquitous' has been also used in terms of solar-powered wearable technology in the work of Shibayama et al., who present a fabrication method of small-sized crystal silicon solar cells for ubiquitous applications and tandem device with perovskite solar cells [21]. In fact, the integration of renewable energy in itself does not guarantee an access to energy in the ubiquitous sense, however, since renewable energy is intermittent and there is a mismatch between supply and demand. Thus, energy storage is factually a more critical component for pervasive energy supply chains than the energy source in itself.

On the other hand, the 'quality of energy to be accessible everywhere' depends strongly on the properties of the distribution system. The need of a pervasive energy distribution system was realized by Nikola Tesla in the beginning of the 20th century. Therefore, he ended up with several innovations related to wireless power transmission (WPT) [22]. The ultimate idea was to make electric power accessible in the way similar to radio broadcastings, which would have set the power transmission and distribution system free from power lines and several other physical infrastructures. Recently, the potentialities of WPT have been particularized, for example, by Liu et al., who suggest decentralized WPT through small-scale power relays and appliances including an appropriate receiver to utilize the wireless power supply [23]. Again, there has been an intention to alleviate the inefficiency and impracticality of energy transmission and distribution based on physical infrastructures by finding solutions, where energy supply and demand are located as close to each other as possible.

2.2. Discussion framework

In this paper, we use the term 'ubiquitous energy' to refer to 'pervasive energy supply chains that guarantee an access to adequate resources of energy and power for all energy users at any moment of time'. The use of this expression is reasonable, since it succinctly describes the essence of energy supply chains with respect to the conceptual background discussed in Section 2.1. However, our review suggests that particularly concerning the physical part of the energy supply chain, quite a little discussion has been dedicated to issues such as the 'quality of energy to be present everywhere' or 'access to energy everywhere and at any moment of time'. On the other hand, 'ubiquitous energy' is rather narrowly understood both as a concept and technology.

To establish a discussion framework for 'ubiquitous energy', we classify energy supply chains by way of two categories, namely, (i) scope and (ii) decentralization. The first category illustrates the



Scope	Segregated (centralized)	Semi-integrated (hybrid)	Integrated (decentralized)
Global	Global energy supply based on large-scale installations both in the outer space (e.g. solar power plant installation in the Earth's orbit) and on the surface (e.g. harvesting super volcanoes for power generation)	Global energy supply based on installations representing various-scales and degree of integration (e.g. solar power installations in deserts, a network of nuclear power plants)	Global energy supply based on simultaneous coordination and management of mainly medium and small-scale energy resources through virtual power plant (VPP)
Local	Energy supply for neighborhoods, districts or towns relying on off-site energy sources	Energy supply for neighborhoods, districts or towns using mainly on-site and nearby energy sources	Building-integrated renewable energy Vehicle-integrated renewable energy
Individual	Charging of mobile appliances (e.g. cell phones) from mains	Wearable solar power generation and integrated battery storage with external charging options (e.g. smart clothes)	Internal energy harvester using the movements and/or heat of human body to energize bio-implants Mitochondrial energy generation in human cells

Fig. 1. Classification of energy supply options with examples.

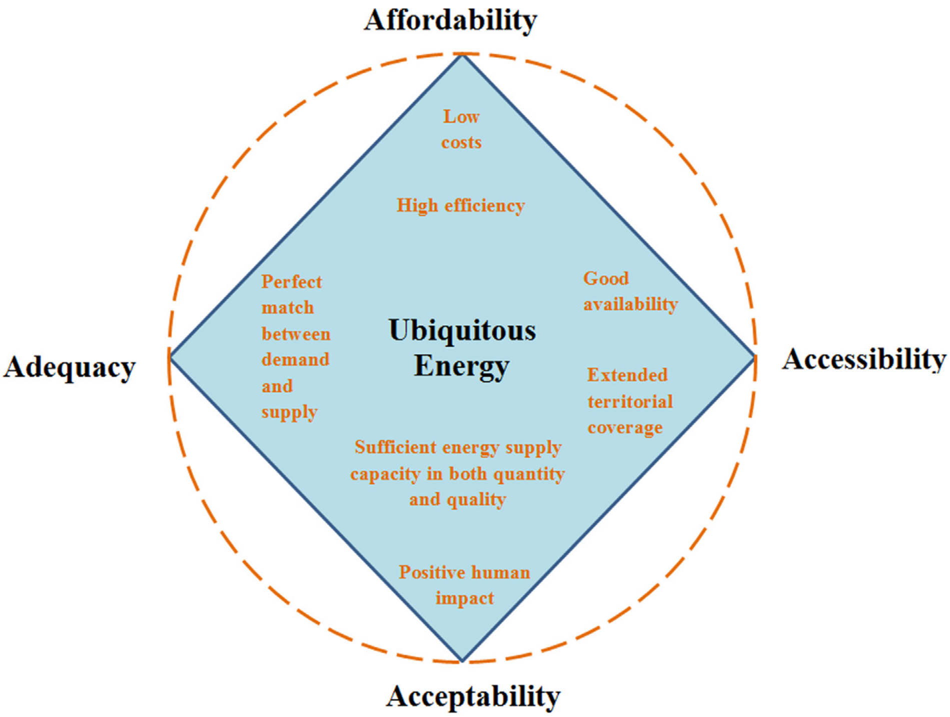


Fig. 2. Main qualities of 'ubiquitous energy'.

scalability of energy supply chains and the second one the distance between an energy source and a demand node. Relying on this classification, energy supply chains can be located on the axes 'small-scale – large-scale' and 'segregated (or centralized) – integrated (or decentralized)'. The aim of this classification is to underline that the concept in itself covers physical systems ranging from very small to very large scopes and energy sources and distribution systems from fully integrated to global-scale energy solutions. Examples of energy supply options in the framework of 'ubiquitous energy' within various scopes and degrees of integration are shown in Fig. 1. The examples have been chosen by the authors according to their own discretion.

In tandem with the scope and integration of the physical energy supply chain, the demand of 'ubiquitous energy' to be present everywhere and any time also sets several requirements for the energy and power resources and technology, which again are consumer-specific. First, it is required that the access to energy covers each square meter of a given region and exists at each moment of time plus there is a perfect match between the supply and demand of both energy and power. Therefore, a sufficient capacity of all the required types of energy (e.g. electricity, heat, cooling, fuels) is available and their quality (e.g. operational temperature, voltage, frequency) matches with the demand. Again, there is a sufficient amount of appropriate (standardized) interfaces to the various energy sources. The energy supply chain is resilient and immune to failures and power outages due to appropriate technologies and sufficient measures against contingencies.

Besides the properties of the physical system and technology, there are other issues constraining the quality of energy being accessible. These include the requirement of the technology being commercially available and mature, affordable in terms of high efficiency, low lifecycle costs (the sum of initial, operational and residual costs), and small footprint. Again, it is presumed that both the technology and related systems enjoy human acceptance and thus an extensive distribution. On the basis of the above discussion, the main qualities of 'ubiquitous energy' are summarized in Fig. 2.

To describe the concept 'ubiquitous energy' in terms of 'quality of energy to be present everywhere', we also conducted a literature research using the web databases (Google Scholar and ScienceDirect databases) and several combinations of keywords including the words 'energy', 'criteria', 'attributes', 'analysis', 'evaluation' or 'assessment' so that the word 'energy' was mandatory within the title, keywords and abstract of the target document. On the basis of the findings, we selected and listed attributes that have been commonly applied to describe the sustainability of energy systems and classified them at our own discretion under the main criteria 'adequacy' and 'accessibility' and to some extent under 'affordability'. Although social acceptability is seemingly an important dimension to realize ubiquitous energy, we didn't include that in our list, since in this paper our intention is to characterize the concept particularly from the perspective of technology. On the other hand, we wanted to save space. The results of the literature study with the key references are listed in Table 1.

3. Technology overview

Energy supply chain is a complicated, dynamic system including not just physical infrastructures and technology, but also information, data and other resources to carry out energy exploration, conversion, transmission, distribution, storage and also end use of energy. In this overview, our main focus is on the physical components of the energy supply chain and on an attempt to identify the key technological pathways to enable the transition towards 'ubiquitous energy'. A detailed review of the state-of-the-art of energy technologies is not provided, since the literature is quite abundant with detailed reviews in specific areas of technology.

Table 2
Framework of technology review.

Technology categories	Technology portfolios
Energy generation technologies	Efficient and light solar PV/T Small-scale CHP Harvesting of kinetic energy Small-scale nuclear power plants, fission and fusion
Energy storage technologies	Rapidly charging and light energy storages Large-scale and seasonal energy storages Affordable hydrogen economy Artificial photosynthesis and synthetic hydrocarbons
Energy transmission/distribution technologies	Wireless power transmission Off-grid and micro-grid solutions

We start the overview by discussing some of the key trends of development regarding the evolution of energy supply chain. Next, we address the latest technological innovations using a systematic framework, where we classify the technologies into three categories according to the structure of the energy supply chain, namely, (i) energy generation, (ii) energy storage and (iii) energy transmission/distribution technologies. Here, the technologies are further classified under each category into the representational groups according to the technology portfolios used in the Radical Technology Inquirer (RTI) of the Committee for the Future of the Finnish Parliament, as shown in Table 2 [32,33]. Finally, we summarize the most relevant technology pathways to ubiquitous energy applying a SWOT analysis to the reviewed technology portfolios.

3.1. Evolution of energy supply chain

The most prominent trend of development in terms of the 'ubiquitous energy' concept is the use of distributed and shared resources. A driving force of this development is the intention to use of low-cost technologies based on local resources according to the needs of the end user. Locally integrated solar energy is becoming financially viable in comparison with the conventional solutions of power and heat generation, whereas the intermittent forms of renewable energy can be stored efficiently by advanced battery technologies, capacitors and the conversion of power into gaseous and liquid fuels. The development of energy storages, integrated off-grid and micro-grid solutions and wireless power transmission are anticipated to challenge the conventional power and heat distribution grids [32,33]. On the other hand, the

Table 1
Main criteria and qualifying attributes of ubiquitous energy.

Main criteria	Qualifying attributes	References
Accessibility	Ability to interact, ability to share, (resource/energy supply) availability, compatibility, comprehensiveness, connectedness, (grid) connectivity, cooperation, deployment time, diversity, ease of decentralization, flexibility, locality, logistical feasibility, (technical) maturity, proximity, safety, scalability, (minimum) size, utilization factor, visibility	[16,18,24–29,31]
Adequacy	Ability to monitor, ability to regulate, capacity, continuity, controllability, (energy) cycling, detectability, (energy) dispatchability, energy self-sufficiency, lifespan, manageability, measurability, non-redundancy, observability, predictability, (power) quality, reliability, (energy) resilience, resource feasibility, (energy) security, (network) stability, traceability, (energy) import vulnerability	[16,24–25,30]
Affordability	affordability, competitiveness, completeness, (capital/energy) costs, efficiency, lifespan, service life	[16,24–26,31]

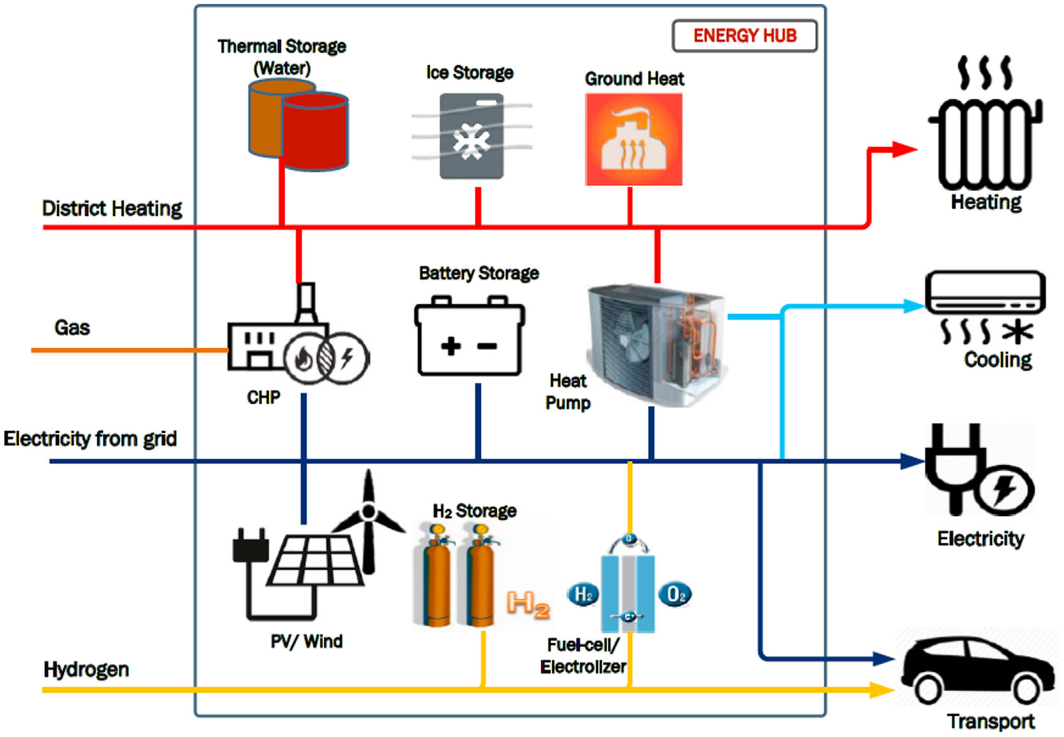


Fig. 3. Illustration of energy hub [36,37].

new energy era is expected to be an era of prosumers, i.e. 'agents that both consume and produce energy' [34].

Even though the physical installations of the energy supply chain represent a variety of scopes, for the reasons above solutions located at the mid-section of the visualization in Fig. 1 will be highlighted in the foreseeable future. Therefore, our overview focuses on decentralized and small-scale rather than centralized and large-scale settings. We anticipate that the concept of 'ubiquitous energy' will be mainly realized through local energy supply chains that serve either communities or single buildings. The trend of development is towards the energy supply chain consisting of a network of energy hubs (EH), where the production, conversion, storage and consumption of different energy carriers take place [35]. Multiple energy carriers meet each other to 'fulfill the demand requirements in an optimal manner', as illustrated in Fig. 3 [36].

The aforementioned energy hub networks, also known as hybrid grids, multi-carrier or multi-vector energy networks, have been particularly envisioned as an appropriate energy supply solution for urban environments, where there is a need to simultaneously supply power, heat, cooling and fuels (e.g. biogas, hydrogen) [38]. Here, the prosumer activity calls for bi-directional interfaces for various energy types. In the sense of technology, the bi-directional access to both electrical and thermal grids is possible using commercial technology. A bi-directional fuel interface is technologically mature, commercially available and permissible (with constraints). The bi-directional grid access is constrained by the quality of energy exported to the grid (e.g. voltage and frequency for power grids, the heat source temperature for thermal grids and factors such methane contents, removal of hydrogen sulphide, carbon dioxide and moisture for fuel grids) [39,40].

The realization of 'ubiquitous energy' will benefit from the concept of 'smart power grid', which is defined as an 'electric power distribution system suitable for plug-and-play of distributed renewable energy and distributed energy storage devices' [41] and considered a community network with standardized communication and interoperability between any appliance and equipment connected to the power grid [42]. Again, the 'smart grid' concept can be generalized into 'hybrid smart grid' by including a multi-carrier energy network, downscaled to local micro-grids or up-scaled to create a network ('Internet of Energy', IoE), which records, shares and analyses dynamic technical, economic and environmental information between all the nodes of the grid [43,44]. Thus, the IoE enables 'virtual power plants' (VPP), where distributed energy resources are integrated and co-operated with an intention to obtain a reliable power supply at a national or regional level [45]. Correspondingly, due to the IoE the national power grid may serve as 'virtual energy storage' to help single prosumers to obtain a zero-energy balance. The information and data to be collected via the IoE may contain several recorded, instantaneous or forecasted data items with various resolutions and accuracies, including variables and parameters such as the dynamic frequency or the dynamic import/export tariffs [46].

Due to the recent development of plug-in electric vehicles with the bi-directional power exchange, the discussion of vehicles as 'mobile energy hubs' (MEH) has become topical. The presence of MEHs will potentially help improving the accessibility to energy to areas with no grid interface, wherefore the topic is relevant from the perspective of 'ubiquitous energy'. So far, the research has been mainly focusing on electrical power exchange between buildings, vehicles and grids [47–49], which again enables the centralized control in the energy utilities and services to the power grid, such as power grid regulation, spinning reserve, peak load shaving, load levelling and reactive power compensation [50]. The vehicle-to-X and X-to-vehicle (V2X, X2V) energy exchange modes have been defined in [51] as depicted in Fig. 4.

A bidirectional power exchange (V2B) is commercially available and provided, for example, by Toyota in their Mirai Fuel Cell Vehicle (FCV). According to the manufacturer's note, a separate adapter allows the car's fuel cell stack to be used to generate back-up electricity with a maximum DC power output of 9 kW. In the literature, however, the term 'mobile energy hub' (MEH) is interpreted to include a V2G technology, which is also mature and commercial. An example is the 'Leaf' model of Nissan. The 'Sfinkx' Energy Generating Vehicle (EGV) has been also mentioned as an MEH, which features a 50 kW mobile PV array to be installed in a truck to energize an on-board Battery Energy Storage System (BESS). An example of a bi-directional wireless charging system for V2G applications with full compatibility with the

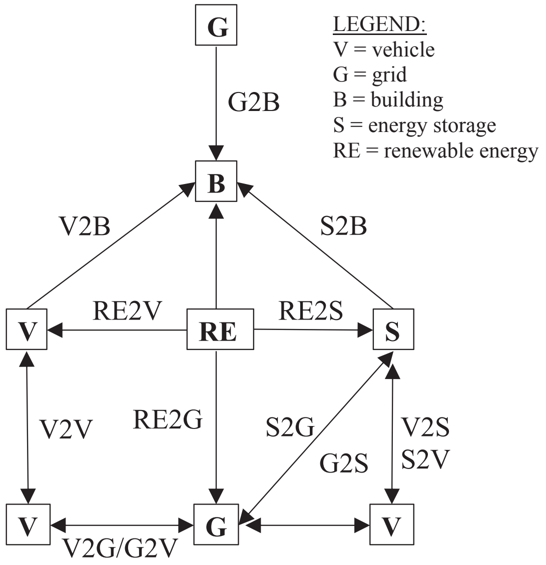


Fig. 4. Energy exchange modes between vehicles and surrounding energy systems.

requirements of the standard SAE J2954 has been presented in [52].

So far, the bi-directional exchange of thermal energy or fuels between vehicles, buildings and grids has been considered more hypothetical than a practical. This type of an approach is shown in our own study, however, where the waste heat released from fuel cell cars and local hydrogen generation plants would be utilized for heating spaces and domestic hot water [53]. Nomura et al. have patented (US patent 7213664) a mobile fuel cell micro-cogeneration unit to generate electricity and domestic hot water. The vehicle is also capable of recovering and storing heat during the drive [54].

Harnessing autonomous vehicles as MEHs will potentially bring a new dimension to the discussion around the ‘ubiquitous energy’ concept. Besides cars, autonomous vehicles may include freighters and trucks, personal transporters, robotic exoskeletons, walking robots, unmanned aerial vehicles (UAV) and ships with no crew on board [55]. Their potential impact on various types of supply chains (including energy) is significant due to improvements in the design, usage, and connectivity of vehicles and transportation systems, such as enhanced options of eco-driving and new opportunities such as platooning of vehicle fleets in tight formation [56]. The number of vehicles may decrease, whereas the driving distance and hence their operational hours would increase [55]. On the other hand, the presence of autonomous vehicles may result in dimming the boundary between housing and transportation. For example, Renault Symbioz is a vision, where an automated vehicle assimilates as a part of a living room, when not in use. This type of interoperability between vehicles and the built environment would eventually convert the V2X and X2V energy exchange and communication more integral than it is in the case of human-driven vehicles.

Since autonomous vehicles will allow the dynamic information to be directly accessed to and downloaded, their control can support the optimization of the energy supply chain in several ways. For example, the time and location of interactions with the fixed energy grids can be optimized. Given that a significant amount of autonomous vehicles is in use simultaneously, the traffic flow can be controlled by restricting the access to energy supply. The use of autonomous vehicles may also offer new tools for energy quality (exergy) management. For example, various temperatures in the vehicle-integrated thermal energy storages could be utilized to adjust the supply and demand of thermal energy within a variety of temperature requirements. From the economic point of view, the charge and discharge cycles of the on-board energy storage could be optimized with the aim at minimum costs and maximum revenues. Again, the vehicles’ intelligence could be used in determining whether energy import or export within a community is necessary or feasible.

Given that the vehicles are applied as integral components of the energy supply chain, the system’s capability to deal with electrical or thermal power in the magnitude of kilowatts or even megawatts is required. The community-scale energy supply is hard to meet using single vehicles due to obvious reasons such as limited capacity of vehicle-integrated renewable energy and energy storage, but also because of the vehicle’s ability to be only situated in one location at once. However, the communication capabilities of automated vehicles allow the development of swarm intelligence. Instead of a single vehicle, an entire fleet of vehicles can be harnessed to manage the energy supply chain, whereas the fleet’s ability to enable the energy supply within a given region would depend on both the amount of vehicles and the number of their operational hours.

The Mobile Energy Internet (MEI) is a novel concept derived by Liu et al. as a merger of the concepts Internet of Energy (IoE) and Mobile Internet (MI) [23]. Their prevailing aim is to solve the problem of wireless power transmission in the ‘last few meters or tens of meters’. Thus, the MEI concept has a significant potential to solve the power supply of numerous applications associated with ‘ubiquitous energy’, such as unmanned aerial vehicles (UAV), body implants, robots and wearable technology and eventually make battery energy storage unnecessary in mobile devices. Presuming that robots and autonomous vehicles also operate as mobile energy hubs, the off-grid access to energy can be extended from tens of meters to tens or even hundreds of kilometres. In tandem with power conversion, storage or WPT options, vehicle-integrated thermal energy generation or fuel synthesis is possible [57]. Hence, it is reasonable to suggest a more generic definition for the MEI as a ‘hybrid smart grid, which enables the exchange of any energy type between static and mobile energy hubs’.

Hypothetical application scenarios of the MEI are shown in Fig. 5. As seen in Fig. 5, the system includes a drone-based mesh network to establish a movable and adaptable wireless power relay network, as Liu et al. suggest in their work [23]. Moreover, the system is equipped with a swarm of MEHs (a mobile robotic power bank system, MRPBS), where battery energy storage systems (e.g. Tesla Powerpack) are integrated in unmanned, autonomous ground vehicles. Here, a pre-defined energy storage capacity within a given region can be maintained by controlling variables such as state-of-charge, location and velocity of the mobile robotic power banks.

3.2. Energy generation technologies

3.2.1. Efficient and light solar PV/T

The sun is factually the origin of all energy received by the Earth, wherefore solar energy can be considered one of the pillars of energy generation within the concept ‘ubiquitous energy’. The identified areas of application of solar photovoltaic energy generation (SPV) are numerous, including solar PV based water pumping, solar PV home lighting systems, solar PV powered desalination plant, solar PV thermal, space technology, building integrated solar PV (BIPV) systems and concentrated solar PV (CPV) systems [58]. Thermal energy can be generated simultaneously with electrical power in solar photovoltaic thermal systems (PV/T), which are efficient for several real-life applications, where the simultaneous demand for thermal and electrical energy exists.

As exemplified in Fig. 1, both the integrated and concentrated harvesting of solar energy may be included in ‘ubiquitous energy’, but with respect to the expected trend towards decentralized solutions, the integrated approach seems to be more useful, since it helps in reducing the need of heavy infrastructures for energy conversion, storage, transmission and distribution. An integrated PV system also reduces the footprint of the system, since it does not only create savings in the need of infrastructures, but also reduces material and space requirement.

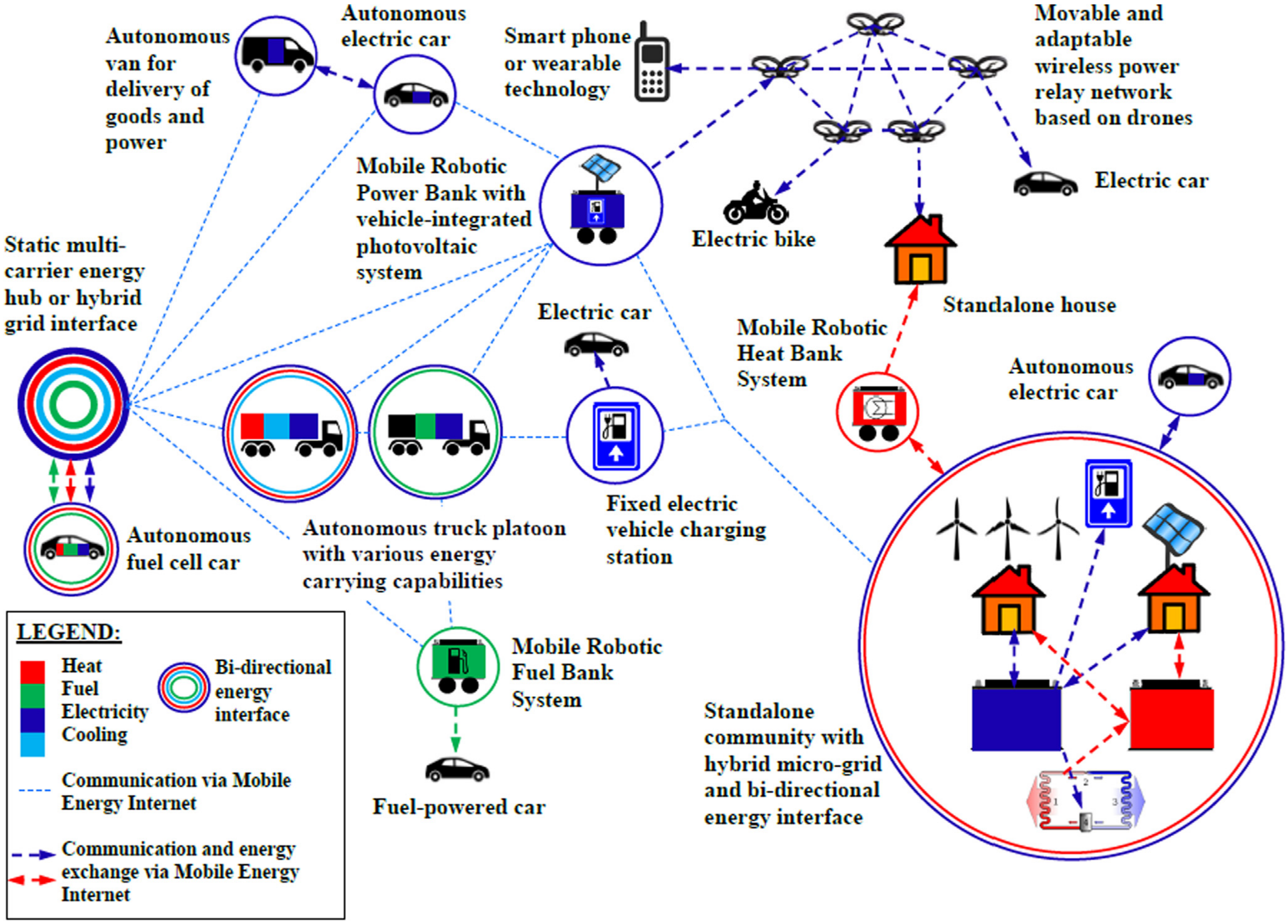


Fig. 5. Application scenarios of Mobile Energy Internet (MEI).

When it comes to the characteristics of solar PV technologies, structural flexibility is one of the key requirements of integrability, whereas the use of light-weight materials enables good transportability. Therefore, a promising short/medium-term solution to realize a ubiquitously integrated renewable energy system is third-generation photovoltaic cell, i.e. high-efficiency thin-film device [59]. The key technology is an organic photovoltaic cell, which provides a light-weight structure and mechanical flexibility. Another attractive technology is polymer photovoltaic cell, which has the potential to exhibit transparency, allowing applications such as windows, walls, or flexible electronics. The reported efficiency of both the aforementioned technologies is 8%, but the technology is yet developing [58]. Lately, efficiencies as high as 15% have been reported [60]. Photovoltaic coatings and paints can be produced at the molecular level, which enables them to be integrated in practically any surface. Other advanced PV solutions with characteristics suitable for ubiquitous integration are copper zinc tin sulphide (CZTS), dye-sensitized photovoltaic cell (DSSC), quantum dot photovoltaic cell (QD), perovskite photovoltaic cell, carbon nanotubes (CNT) and ‘hot carrier’-based PV [35]. The evolution of photovoltaic (PV) cell efficiencies is regularly published by the National Renewable Energy Laboratory (NREL) [61]. The state-of-the-art in 2018 is depicted in Table 3.

Several innovative ways to integrate solar PV technology are reported in the literature in the framework of ‘ubiquitous energy’. An example of building-integrated PV have been provided by the Tesla Company in terms of their solar roof made of a textured glass tile with integrated solar cells and the Virte Solar company with their roof-integrated thin-film solar cells. The ‘Ubiquitous Energy Inc.’ company, in turn, develops transparent solar cell technology for mobile applications and smart windows. Their ClearView Power™ is a thin-film technology capable of maintaining up to 90% visible transparency. An example of a vehicle-integrated solar PV is the Ford C-max Solar Concept. The car’s roof is covered by a 1.5 m^2 solar PV system, but the solar yield is boosted by a Fresnel lens concentrator, which multiplies the exposure area. The Fresnel lens concentrator of 20.6 square meters is provided as a carport. When the car is parked under the Fresnel lenses and the concentrated sunlight hits the solar photovoltaic cells on the roof of the car, the yield is estimated by the manufacturer to be sufficient to charge up an average vehicle battery pack on a daily basis. Again, a kilometer-long stretch of solar roadway has been tested in Jinan city, China. The Jinan Ring Expressway consists of three layers, namely, insulating layer on the bottom, transparent concrete on the top and photovoltaic panels in the middle. With approximately 5874 square meters, the total installed capacity of the solar roadway is 800 kW. The solar roadway is also designed for wireless charging of electric vehicles in the future. Similar projects have been also reported from Sweden and the Netherlands, albeit without the possibility of wireless charging. Solar PV can be also integrated in the built environment by way of solar trees, which by imitating the shape of the plants help in reaching the best integrability and the optimal systemic efficiency [62].

Concentrated solar PV (CPV) commonly refers to collecting the beam radiation by way of technologies such as parabolic dish, linear Fresnel, dish/engine and power tower, which concentrate the radiation solar PV panels or into a thermal process capable of converting heat into power [63]. The conversion may also be implemented as separate thermal power or by way of thermo-electric conversion (Seebeck effect). On the other hand, concentrated solar energy can be also harvested by way of technologies installed in the Earth orbit. Those are, for

Table 3
Best research-cell efficiencies in 2018 by NREL [61].

Technology	Organization/ Institute/Product	The state-of-the-art efficiency
Multijunction cells (2-terminal, monolithic):		
Three-junction (concentrator)	Sharp (IMM, 302x)	44.4%
Three-junction (non-concentrator)	Sharp (IMM)	37.9%
Two-junction (concentrator)	NREL (38.1x)	35.5%
Two-junction (non-concentrator)	LG Electronics	32.8%
Four-junction or more (concentrator)	Fraunhofer ISE / Soitec	46.0%
Four-junction or more (non-concentrator)	Boeing Spectrolab (5-J)	38.8%
Single-Junction GaAs:		
Single crystal	LG Electronics	27.8%
Concentrator	LG Electronics	29.3%
Thin-film crystal	LG Electronics	28.8%
Crystalline Si Cells:		
Single crystal (concentrator)	Amonix (92x)	27.6%
Single crystal (non-concentrator)	ISFH	26.1%
Multicrystalline	Fraunhofer-ISE	22.3%
Silicon heterostructures (HIT)	Kaneka	26.6%
Thin-film crystal	Fraunhofer-ISE	21.2%
Thin-Film Technologies:		
CIGS (concentrator)	NREL (14.7x)	23.3%
CIGS	First Solar ZSW	22.6%
CdTe	First Solar ZSW	22.1%
Amorphous Si:H (stabilized)	AIST	14.0%
Emerging PV:		
Dye-sensitized cells	Sharp	11.9%
Perovskite cells (not stabilized)	KRICT	22.7%
Organic cells (various types)	Hong Kong UST	11.5%
Organic tandem cells	UCLA-Sumimoto Chem.	10.6%
Inorganic cells (CZTSSe)	IBM Hong Kong	12.6%
Quantum dot cells (various types)	NREL	13.4%

example, space solar power satellite systems (SSPS) that collect and convert solar irradiation to electric power in space and transmit the electric power to earth wirelessly [64]. Since the power beams can be directed from the orbit to the regions where the sun is not shining, particularly SSPS-based systems would potentially improve the access to instantaneous solar power, thus being worth considering with respect to the 'ubiquitous energy' concept.

3.2.2. Small-scale CHP

The evolution of the energy supply chain towards hybrid smart grids capable of supplying multiple types of energy favors the implementation of hybrid systems, which include simultaneous generation of electricity and heat (cogeneration, combined heat and power, CHP) and simultaneous generation of several types of energy (tri-generation of poly-generation) [65,66]. In the context of 'ubiquitous energy', micro-scale and small-scale solutions are useful, because they can be integrated as an energy source for a variety of applications including vehicles and portable equipment. In the European Directive 2004/8 EC, the CHP systems have been classified into three categories according to their maximum rated power, namely, 'micro-cogeneration' ($< 50\,kW_e$), 'small-scale cogeneration' ($50\,kW_e \ldots 1\,MWe$), and 'cogeneration' ($> 1\,MW_e$) [67].

The core of a cogeneration, poly-generation or hybrid system is the prime mover, which converts the primary energy into multiple energy forms. There is a diversity of prime movers, including internal combustion engines, micro-turbines, Stirling engines, steam engines and turbines (organic Rankine cycle, ORC), thermoelectric generators and fuel cells [e.g. 68,69]. Internal combustion engines represent a mature technology, which operate at a relatively high efficiency but with a limited portfolio of primary energy sources. Micro-turbines are an emerging technology with a relatively high efficiency, whereas Stirling engines, steam engines, ORC engines or turbines and thermoelectric generators accept a variety of primary energy sources from fuels and waste heat to concentrated solar beams [69]. The physical dimensions of the smallest micro-cogeneration plants are less than 1 m, which is comparable with the dimensions of household appliances. However, fuel cells can be applied for even smaller scopes, such as a power source of a cell phone.

The scalability and integrability of fuel cells makes them exceptionally attractive for 'ubiquitous energy'. Due to the significant research efforts, partly pursued by the car industry, they also represent mature enough a technology for sustainable energy transition. Specifically, the success of fuel cell technology is based on its ability to hybridize with natural gas systems and micro-turbines plus the utilization of biofuels and affordable catalysts, such as nickel [32,33].

Some of the characteristics of the prime movers for micro-scale cogeneration are listed in Table 4 on the basis of [69–71].

Table 4
Characteristic qualities of small-scale CHP technologies [69–71].

Technology	Efficiency in CHP applications (LHV)	Theoretical power output at minimum	Integrability (including domestic CHP)	Controllability	Maturity
Internal combustion engine	Electrical: 25-% Thermal: 60-% Total: 85-%	Hundreds of watts	Various heat recovery options, bidirectional grid interface or battery energy storage	Quick response, easy control, adjustable part-load operation	Commercial technology
Stirling engine (external combustion engine)	Electrical: 10–20% Thermal: 75% Total: 65–95%	Hundreds of watts	Hydronic heating system via buffer storage, bidirectional grid interface or battery energy storage	Delayed startup/shutdown, ON/OFF control	Emerging technology, early market
Micro-turbine	Electrical: 15–30% Thermal: 60% Total: 60–80%	Kilowatt(s)	Various heat recovery options, bidirectional grid interface or battery energy storage	Delayed startup/shutdown, limited part-load operation (requires adjustable burning)	Mature technology, market not established
ORC	Electrical: 10% Thermal: 55–70% Total: 65–80%	Hundreds of watts	Hydronic heating system via buffer storage, bidirectional grid interface or battery energy storage	Delayed startup/shutdown, limited part-load operation	Developing technology, early market
Rotary steam engine	Electrical: 9% Thermal: 77% Total: 86%	Hundreds of watts	Hydronic heating system via buffer storage, bidirectional grid interface or battery energy storage	Delayed startup/shutdown, ON/OFF control	Developing technology, not common in the market
Thermoelectric generator	Electrical: 9% Thermal: 77% Total: 86%	Watts	Various heat recovery options, bidirectional grid interface or battery energy storage	Delayed startup/shutdown, ON/OFF control	Developing technology, not common in the market
Fuel cell technology (SOFC, PEM)	Electrical: 30–70% Thermal: 40% Total: 60–80%	Watts	Hydronic heating system via buffer storage, bidirectional grid interface or battery energy storage	Delayed startup/shutdown, limited part-load operation	Developing technology and market

3.2.3. Harvesting of kinetic energy

Various movements and motions take place every moment and everywhere in the geosphere. Kinetic energy harvesting is a generic name for methods and applications to utilize the kinetic energy of these motions in the sense of 'ubiquitous energy'. The most traditional applications of kinetic energy harvesting are wind, hydro and wave power, but similar potential is incorporated in any natural or artificial motion of any material, including the movements of the Earth's crust and machinery. Energy conversion into electricity may take place directly or through various other forms of mechanical energy and magnetism. A drawback of kinetic energy harvesting methods is their limited power control, which results in the need of electrical energy storage.

Conventionally, wind energy has been harvested through fixed installations on the ground, built environment or offshore. A promising trend of development is wind energy harvesting through bladeless or vertical wind turbines and airborne wind power plants operating in high altitudes, which potentially extends the accessibility to wind power to new areas and closer to end users [72,73]. The latest development is exemplified by the Wind Airborne Tethered Turbine System (WATTS) of the Sky Windpower Corporation, which uses Flying Electric Generators (FEGs) capable of not just converting high altitude wind energy into electricity, but also transmitting power to ground stations via tethers and carrying payloads for various purposes. The FEGs can operate at altitudes up to 600 m and reach areas that are inaccessible with other than airborne systems.

The utilization of piezo-, tribo-, and pyroelectric phenomena is becoming popular in small-scale energy harvesting by way of nanogenerators [74,75]. Here, piezo- and triboelectric effects refer to the conversion of mechanical energy directly into electricity, whereas the pyroelectric effect harvests electrical power from temperature fluctuations. Piezoelectricity is commonly exhibited in strong but rigid quartz crystals useful for applications such as floors or shoes [76,77]. However, the development of modified graphene allows the generation of electrical current by bending the material. The technology of nanogenerators can be also made transparent. Hence, the energy harvesting through nanogenerators would be particularly attractive in ubiquitous energy generation integrated in clothes [78]. Simultaneous piezo-, tribo- and pyroelectric energy harvesting is another emerging trend of development. Hybridized implementations have been suggested by Ricoh in their 'Energy-Generating Rubber' and by the researchers of the University of Oulu in the KBNNO material [79]. Again, Liu et al. present a hybrid solution, which recovers power from sunlight and raindrops by way of an integrated silicon solar cell and a triboelectric nanogenerator [80].

Promising steps have been also taken among technologies utilizing phenomena such as magneto-elasticity and the Brownian motion. Magneto-elasticity occurs in Galfenol, which is an alloy consisting of iron doped with the metal gallium. Doumann et al. have observed that Galfenol is able to turn up to 70% of mechanical energy into magnetic energy [81]. The findings might enable, for example, the development of novel type of collision detectors for vehicle applications. Another potential, yet a laboratory-level method to convert kinetic energy directly into electricity is the Brownian motion in graphene. Vibration Energy Harvester (VEH) is an experimental setup that consists of a sheet of negatively-charged graphene suspended between two metal electrodes. The metamorphosis of the sheet of graphene invokes an alternating contact between the electrodes, creating an alternating current [82]. The VEH is expected to be useful in several applications of wearable technology.

3.2.4. Small-scale nuclear power plants, fission and fusion

So far, nuclear power has been commonly planned and constructed as a centralized energy solution, since conventional nuclear fission-based power plants have feasible as large-scale installations (electrical power > 1 GW_e). Recent studies suggest, however, that the trend of development is towards small-scale (electrical power < 0.3 GW_e) and mass-produced nuclear power plants and thus improved opportunities in terms of energy generation in the scope of districts or communities. Presuming that challenges such as the waste treatment and expensive risk management will be solved, small-scale nuclear fission power plants may enable a new option to open an access to energy to new regions with reasonable costs and hence contribute to the emergence of 'ubiquitous energy'.

Small Modular Reactors (SMR) within the size of down to 10 MW_e have been proposed to cogeneration (power + district heating) in Finland [83]. NASA has designed their 'Kilopower' fission reactors in the range of 1–10 kW_e to meet the power requirements of a spacecraft or lander [84]. The conversion of nuclear heat to power is based on Stirling engine technology and the reactor is potentially useful also in terrestrial applications. As an alternative to power generation and district heating, applications such as water desalination and hydrogen production have been proposed for small-scale nuclear reactors based on nuclear fission and mature technology [85]. Innovative applications of nuclear fission technology, such as Terrapower LLC's the Traveling Wave Reactor (TWR), are also being developed [86].

Nuclear fusion is often described as an ultimate energy solution due to a virtually inexhaustible energy supply, limited risks of proliferation, and no risks of meltdown [87]. Even though the commercialization of fusion energy is not in sight before 2050, both states and private investors have shown growing interest in the research and development of small-scale fusion reactors. Therefore, it should not be forgotten as an alternative to nuclear fission-based power plants when discussing the energy supply options for the post-fossil energy era. An example of the recent developments in small-scale fusion reactor technology is the 200 MW_e Lockheed Martin Compact Fusion Reactor Concept. Fusion technology has been also developed by companies such as Helion Energy, General Fusion and TAE Technologies (formerly Tri-Alpha Energy). Interest in reactor topologies has also become more versatile, Stellarator-type design being an option to Tokamak reactors [88].

3.3. Energy storage technologies

Energy storage technology enables storing energy for use at a later moment of time and also being transported from one location to another, wherefore it is apparently one of the most critical aspects of 'ubiquitous energy'. Both short-term (hourly or daily) and long-term (seasonal) storages are required for multiple types of energy including various qualities of electrical, thermal and chemical energy. Preferred are integrated, transportable and scalable solutions with high power charge and discharge capacity, high efficiency, and long life span. The key power storage technologies include the options of battery energy storage (BES), superconducting magnetic energy storage (SMES), flywheel energy storage (FES), ultra (or super)-capacitor energy storage (UCES) and various hybrid technologies, such as combined high-energy battery and high-power ultra-capacitor hybrid energy storage [89]. Cryogenic energy storage (CES) is a generic name for a group of technologies capable of storing energy at cryogenic temperatures (below −150 °C at a pressure of 1 bar) in high-pressure gases [90]. The storage can be discharged by expanding the gas to generate electricity in a gas turbine system. Electricity can be also stored as fuels such as electrolytic hydrogen, methane or methanol. These substances, sometimes mentioned as 'solar fuels', can be stored in compressed gas, liquid or metal hydride tanks [91,92]. Thermal storages are classified into sensible, latent and thermochemical storages. They can be also categorized according to their temperature level into industrial cooling (below −18 °C), building cooling (at 0–12 °C), building heating (at 25–50 °C) and industrial heat storage (higher than 175 °C) [92].

Some of the most cited energy storage technologies with their state-of-the-art ubiquity characteristics have been listed in Tables 5 and 6. Please note that the data include both short and long-term energy storage options.

Table 5
Characteristic qualities of electrical energy storage technologies [93–118].

Technology	Scalability	Rate of self-discharge, %/d	Specific weight, kg/kWh	Operational temperature	Mean time between failures, h	Life-span, y	Life-span, cycles	Maintenance characteristics	Specific power, W/kg	Energy efficiency, %	Energy density, Wh/L
Battery energy storage (Li-ION)	Extensive range of applications	0.1…0.3	5…13	−20…+50C	80,000	10…15	1000…5000	Maintenance-free	800	90	300…350
Battery energy storage (Lead-acid)	Extensive range of applications	0.1…0.3	25…30	−30…+40C	< 80,000	5…15	1500…5000	Maintanance cycle 3–6 months	250	85	80…90
Battery energy storage (Flow battery)	Extensive range of applications	0	20…100	+10…+40C	N/A	10…15	2000…10000	Relatively complex structure	90…110	65…85%	20…50
Energy storage in capacitors	Short-term energy storage	2…3	200…2000	−20…+65C	> 100,000	5…10	> 50,000	Low maintenance	> 2000	> 95%	2…10
Flywheel energy storage	Short-term energy storage	20…100	30…100	up to +60C	> 100,000	15	> 20,000	Low maintenance	400…1500	85…95%	20…80
Hydrogen energy storage	Extensive range of applications	0	< 12	0…100C	< 500	10…20	> 1000	–	500…800	35…45%	800–2500
Compressed air energy storage	Extensive range of applications	0	15…30	> 0C	> 30000	20…40	8000…12000	Maintenance cycle > 12 months	< 24	40…70%	3…6
Pumped hydroelectric energy storage	Large-scale solution for both short-term and long-term energy storage	0	700…2000	0…100C	> 30000	40…60	10000…30000	Maintenance cycle > 12 months	0.01…0.12	70…85%	1…2
Solar fuel energy storage	Medium or large-scale solution for both short-term and long-term energy storage	0	< 1	> −20C	–	–	–	–	–	20…30%	500…10000
Superconducting magnetic energy storage	Short-term energy storage	10…15	13…2000	4…140 K	> 100,000	20…30	> 20,000	Low maintenance	0.5…2	> 95%	0.2…5

3.3.1. *Rapidly charging and light energy storages*

With the presumption that decentralized and integrated solutions prevail in the new energy era, rapidly charging and light-weight power storage technologies are attractive for ‘ubiquitous energy’, since they are suitable to be used in vehicles, mobile devices and wearable technology. These technologies are useful in short-term storage of intermittent renewable energy, which increases the self-sufficiency of energy in remote areas.

In the scale of portable devices, the energy conversion and storage can be integrated, for example, using an ionic thermoelectric supercapacitor [123]. Here, a strong ionic Soret-effect in a polymer electrolyte enables thermoelectric heat-to-power conversion at Seebeck coefficients as high as 10 mV/K, which signifies several times more energy than in conventional thermoelectric generators (e.g. for Seebeck coefficient of silicon < 0.5 mV/K). On the other hand, some recent experiments show that the figure of merit of thermoelectric generators could be increased by exposing them to a strong magnetic field [124]. Supercapacitors can be also integrated with a solar cell by way of wearable energy-smart ribbons to simultaneously harvest and store energy [125]. The highly flexible and weavable fabric made using these ribbons is able to generate the energy density of 1.15 mWh/cm^3 and a power density of 243 mW/cm^3, which is sufficient for powering wearable electronics.

The integrability of power storage technologies can be improved by using novel materials (e.g. carbon nanotubes, carbide derived carbons, onion like carbons and graphene) with easy deposition at the layer thickness varying from few tens of nanometers up to micrometers. Hence, the technology can be integrated with complex systems including energy harvesters and functional devices in a way essential for pervasive energy [126]. Again, in applications where energy conversions are needed between various energy types, the rapid development of power electronics technology has realized improved conversion efficiency.

To enhance the energy density (and to reduce the specific weight) of batteries, one of the most cited approaches is the metal-air battery technology, which includes the idea of allowing the metal ions to react with oxygen on the surface of the electrode, thus making the capacity of the battery depend on the surface area of the electrode instead of its volume. Lithium-air technology, for example, allows the theoretical energy density of more than 2…3 kWh/kg (0.3…0.5 kg/kWh), which is several times better than the energy density of the best lithium-ion batteries: 0.25 kWh/kg (4 kg/kWh) [127]. It has been also demonstrated that the use of a graphene–silica assembly (graphene ball) as an anode material would elevate the energy density of a lithium-ion battery to 800 Wh/L, which is more than twice as much as in the state-of-the-art topologies [128].

To make charging faster, producing the electrodes of lithium titanate hydrates has been proven as a workable solution. Here, the battery can be fully charged within 100 s and sustain more than 10,000 cycles, whereas the capacity only degrades by 0.001% per cycle [129]. The specific power of 3000 W/kg has been obtained in aluminium-ion batteries by using an aluminium metal anode and a three-dimensional graphitic-foam cathode [130].

The concept ‘ubiquitous energy’ may also include the idea of harvesting local renewable and sustainable materials in technology manufacturing. The BioSolar company proposes the cathode of a lithium-ion battery to be constructed of a novel polymer (instead of graphite), which they claim to allow the energy density of 0.459 kWh/kg (2.2 kg/kWh) and the costs of $54/kWh, which is one fourth of the price of the Tesla Model S battery. The cellulose of trees can be converted into the building blocks for supercapacitors by adjusting the amount of argon in the pyrolysis [131]. The use of affordable hemp fibres as the material of supercapacitors instead of graphene has been also suggested [132]. Again, the life span of batteries can be remarkably extended by novel approaches. The life span of 200,000 cycles has been obtained by using a non-fragile gold nanowire coated with a manganese dioxide shell and

Table 6
Characteristic qualities of thermal energy storage technologies [119–122].

Technology	Rate of self-discharge, %/d	Specific weight, kg/kWh	Energy density, Wh/L	Operational temperature, °C
PCM thermal energy storage	0	3…50	150–310	0…60
Building Inertia Thermal Energy Storage	100	–		~20
Water heat storage	50	> 10	20–50	0…60
Thermochemical energy storage	0	2…8	250–1000	200…400
Thermal oil storage	50	> 20	40–55	12…400
Molten salt/eutetic mixture	50	> 25	70–80	120…600
Liquid metals	50	> 40	20–40	100…1500
Aquifer	0	–	30–40	5…30
Borehole/cavern/mine	0	–	15–30	5…30
Pit storage	0	–	10–50	5…60

placing it in Plexiglas-like gel electrolyte sheathing [133].

In the category ‘rapidly charging and light energy storages’, the portfolio of thermal energy storage technologies in comparison with power storage options is limited. Sensible heat storages suitable for vehicle-scale, rapidly-charging and discharging applications mainly rely on water storage tanks. Here, the operation is constrained by the effectiveness of the heat exchanger and the storage temperature, which may vary between 0 and 100 °C. However, the applicability is well enough regarding the temperature level of interior cooling (at 0–12 °C) and heating (at 25–50 °C) [93]. A promising and abundantly cited latent heat storage technology with high energy density and integrability in both static and mobile applications is phase-change material (PCM) [92,134]. The limited heat release rate of PCM can be improved for rapidly charging applications by mixing the PCMs with matrix of high thermal conductive materials [135].

3.3.2. Large-scale and seasonal energy storages

Large-scale and (inter-)seasonal energy storages are required to improve the temporal access to intermittent renewable energy in community-scale applications. They are commonly referred to as a method to store solar energy in summer to be used in winter. These solutions are fixed rather than mobile, and they can be integrated as a part of communities’ energy systems, which makes them a crucial contributor to utilize on-site renewable energy resources efficiently and to ensure the adequacy of energy in all circumstances. Both grid-connected and stand-alone or micro-grid-based solutions are allowed. In the large scale, integrated power conversion and storage options have been proposed, for example, to be integrated with wind power plants, which utilize pumped hydroelectric or compressed air energy storage. In the case of off-shore wind power, underwater compressed air energy storage has been introduced [136]. Cryogenic energy storage technologies, such as liquid air energy storage (LAES), have been mentioned as appropriate for mid- and large-scale applications [90].

In the evolution of large-scale battery energy storage technologies, factors such as costs and recyclability are highlighted. One of the possible solutions is the sodium-magnesium (Na-Mg) hybrid battery, which is fully based on materials abundantly available on the Earth [137]. Affordable materials suitable for large-scale power banks are urea, aluminum, graphite, sulfur, water, salt and water-soluble organic redox-active materials (for flow batteries) [138–140]. The recent development of the cost-efficient zinc/manganese oxide battery technology supports the large-scale applications [141]. The cost of battery technology can be also combated by automated serial production in remarkable scale (e.g. Tesla Gigafactory) or by recycling used batteries from electric vehicles [142].

In the large-scale thermal energy storage, one of the key trends is heat storage into the ground. There is a variety of solutions including borehole thermal energy storage (BTES), energy pilings and pit storage [119]. The aquifer thermal energy storage (ATES) allows the use of ground water in intensifying the heat transfer and managing the aquifer temperatures to maintain the maximum systemic coefficient of performance. The applicability of ground thermal energy storages is constrained by the thermo-geological properties of the ground, wherefore the implementation of the technology in the ubiquitous settings is a potential challenge. The above-ground storage options, such as water tanks, are unfavorable for long-term storage due to their large space requirement and heat losses even though effective solutions for insulation (vacuum insulation panels, aerogels) are being developed. In principle, the problem of the heat loss could be also solved through latent heat storages (LHS) or thermo-chemical materials (TCM), which store and release heat by a reversible endo-/exothermic reaction process, but the technology is still in the experimental phase and there is a scarcity of information related to its applicability in practical systems [143].

Due to their significant energy density, the use of solar fuels, particularly electrolytic hydrogen, has been suggested as a preferred solution for seasonal energy storage [144]. Separate technology portfolios (Sections 3.3.3 and 3.3.4) have been dedicated in this paper for storing energy in fuels.

3.3.3. Affordable hydrogen economy

The lack of affordable hydrogen conversion and storage options has been the bottleneck for the implementation of hydrogen economy, i.e. harnessing hydrogen as an energy carrier within the energy supply chain. The methods have been proven out to be technically challenging, inefficient and costly particularly in the context of decentralized and small-scale applications, such as every-home re-fueling stations.

At the moment, the majority of hydrogen is produced from fossil fuels using well-established and large-scale solutions such as steam reforming, gasification and partial oxidation, whereas water splitting into hydrogen and oxygen will most likely be the source of hydrogen in the new energy era. Water electrolysis through proton exchange membrane electrolysis (PEM) is a mature, efficient (conversion efficiency of up to 85%) and scalable solution based on fuel cell technology, which, unfortunately, has been plagued by expensive materials, such as platinum. The cost of fuel cells and electrolysers can be dropped, however, by optimizing the manufacturing process in terms of reduced platinum contents and improved assembly of components through advanced simulation models [145].

The alternative approach, i.e. anion exchange membrane electrolysis (AEM), allows the replacement of conventional noble metal electro-catalysts with low-cost transition metal catalysts, wherefore it has been suggested for low-cost hydrogen production over the past few years [146]. Nickel has been identified as an affordable alternative to platinum as a catalyst material, whereas promising solutions to replace platinum are nitrogen-doped carbon nanotubes (CNTs) and modified graphene nanoribbons [147].

Other options include thermochemical and photo-catalytical water splitting into hydrogen and oxygen. The thermochemical method requires high temperatures (800–2000 °C), which can be generated by recovering heat from concentrated solar or nuclear power plants [148,149]. A scalable option for ubiquitous energy would be photocatalysis that converts solar energy directly into hydrogen by using TiO_2 as a photocatalyst [150]. The method is affordable in principle, but its conversion efficiency is low (< 5%) at the present stage of development, anyway.

Sodium Silicide (NaSi) is a chemical compound that reacts with water at atmospheric conditions, hydrogen gas being the outcome of the reaction. In the ubiquitous energy system, compounds like NaSi could be used, for example, as a hydrogen source for portable fuel cells [151]. Sieving hydrogen gas out of the atmosphere by a one-atom-thick graphene membrane has been proven possible [152].

Hydrogen can be also produced from biomass through various methods including fermentation, gasification and photosynthesis (micro-algal hydrogen production) [153 –157]. These methods are under intensive research, and more information is needed, for example, about their affordability, scalability and integrability in the context of ubiquitous hydrogen economies.

The storage of hydrogen in gaseous form is the present-day commercial solution, but it includes the risk of explosion and leakages. High pressures (350 bar or 700 bar) are required to keep the storage volume reasonable (30–40 g/L). Hydrogen can be also stored in liquid form (70 g/L at −253 °C), but a powerful cooling system and insulation are required to prevent the storage from any heat input from the surroundings and thus the evaporation of the hydrogen [158]. Hence, gas or liquid H_2 cannot be considered economically viable options in terms of ubiquitous hydrogen storage [159].

Remarkable research efforts have been dedicated to hydrogen storage recently, as well. The most cited alternative of physical hydrogen storage (gas or liquid) is the idea of absorbing hydrogen in a dense enough form into some structure. This so called materials-based hydrogen storage may utilize the phenomenon called physical sorption (physisorption) in porous materials (zeolites, carbon structures, and metal–organic frameworks) or chemical sorption (chemisorption) in metal or chemical hydrides [159]. The storage capacity of 70–150 g/L is obtained depending on the storage method, but there are several challenges related to issues such as working pressure and temperature. For example, several physical sorption materials require cryogenic temperatures (77 K) and high pressures (50–100 bar) to keep the storage capacity reasonable [160]. The recent interest in hydrogen-powered vehicles seems to have increased the interest in organic chemical hydrides (OCH) that may act as liquid hydrogen carriers under normal temperature and pressure. These include compounds such as methylcyclohexane, toluene, ammonia, benzene, methanol and formic acid [161–163]. The applicability of novel materials has been investigated, including Lithium Hydrazinidoborane, carbon nanotubes and nanoporous materials [160,164,165].

3.3.4. Artificial photosynthesis and synthetic hydrocarbons

Synthetic fuels are proposed as an alternative to hydrogen in converting solar radiation into storable energy. Thus, such energy carriers and chemical reactions are under investigation that overcome hydrogen in storability and distributability and are yet cleaner than fossil fuels. Presumptively, these are liquid hydrocarbons, which are easy to store in containers of various sizes and are useful in scalable technologies such as combustion engines or fuel cells. Sunlight or electricity may be used as the source of energy. Given that the supply chain is appropriately designed, the conversion process does not disturb the global carbon balance and thus enables carbon-neutrality.

The most cited mechanism in the above context is photosynthesis, i.e. a light-catalyzed chemical reaction that converts carbon dioxide and water into large organic molecules. Each green plant on the Earth applies photosynthesis, wherefore the mechanism in itself is pervasive in essence. To develop affordable technologies of appropriate space requirement and integrability, the challenge is to efficiently capture and convert solar energy into solar fuels using modified photosynthetic systems and catalysts, wherefore the mechanism is known as artificial photosynthesis [166].

In systems based on natural photosynthesis, such as microalgae bioreactors, the solar-to-fuel efficiency commonly remains less than 5% [167]. By combining the hydrogen-oxidizing bacterium *Ralstonia Eutropha* with a cobalt-phosphorus water-splitting catalyst, Liu et al. have succeeded in obtaining the solar-to-isobutanol efficiency of up to 10% [168]. Sakimoto et al. taught the natural, nonphotosynthetic bacterium, *Moorella thermoacetica*, to cover itself by cadmium sulfide (CdS) nanoparticles, which act like solar panels. The hybrid organism, *M. thermoacetica-CdS*, is able to produce acetic acid from CO_2, water and light at the solar-to-acetic acid efficiency of above 80% [169].

It has been also shown that the artificial photosynthesis can be triggered in synthetic materials. Uribe-Romo et al. found a mechanism to convert CO_2 into two carbon-based solar fuels (formate and formamides) in metal-organic frameworks (MOF) [170]. The suggested solution is well scalable and integrable. In principle, it would allow homeowners to install a shingle on the roof, which cleans the air while simultaneously converting solar energy to fuel.

Biosynthesis is an alternative method to produce complex organic molecules through an enzyme-catalyzed process. A synthetic metabolic pathway based on a thioesterase specific for butyryl-acyl carrier protein (ACP) for producing renewable propane using the bacterium *Escherichia coli* is introduced by Kallio et al. [171].

Solar-driven photocatalytic conversion of CO_2 into fuels has also attracted a lot of research interest. To that end, Niu et al. design and synthesize a spongy nickel-organic heterogeneous photocatalyst enriched with Rh or Ag nanocrystals to generate formic acid and acetic acid [172]. Song et al. have developed an electrochemical process that uses tiny carbon and copper spikes to turn CO_2 into ethanol [173]. Asadi et al. have integrated electrochemical catalysts into nanometer-scale flakes to convert CO_2 into carbon monoxide (CO) [174]. Again, using a copper-based catalyst, large quantities of ethanol can be produced from carbon monoxide at room temperature [175].

Research and development efforts towards productizing the fuel synthesis mechanisms in portable scale have been reported. Shahparnia et al. have developed micro-photosynthetic cell technology that can harness electrical power from the photosynthesis and respiration of blue-green algae [176]. Their power cell has an open-circuit voltage of 993 mV and the peak power of 175.37 μW, which makes it suitable as a power source for small-scale and wireless applications. The Ineratec company has introduced a chemical reactor technology able to convert power to several gaseous and liquid fuels. Turan et al. have conceptualized an integrable thin-film concept for scaling up the artificial photosynthesis to large areas [177]. The concept has a solar-to-fuel efficiency of 3.9%.

3.4. Energy transmission and distribution technologies

3.4.1. Wireless power transmission

The key mission of wireless power transmission (WPT) is to allow an access to power for such appliances and equipment that are otherwise inaccessible, wherefore it can be considered one of the key technology portfolios for the concept ‘ubiquitous energy’. The potential applications may vary from a link of the energy supply chain for biomedical implants to the electrification of aircrafts. Factually, WPT is a generic term that refers to a multitude of technologies for transferring power from a transmitter (connected with the power source) to a receiver (connected with the load) by way of time-varying electro-magnetic fields. The key challenge in terms of pervasive energy systems is the low power transfer efficiency at long distances, which depends on the operating frequency in a directly proportional manner [178]. First and foremost, the technology may not expose humans and eco-systems to the health and environmental risks.

When the power transfer capacity in the magnitude of kilowatts is required, as in the case of electrical vehicles charging, the most preferred WPT scheme is magnetic resonant coupling (MRC), which is capable of transmitting useful amounts of power both safely for the human beings and at acceptable efficiency [179]. It is worth a remark that at distances less than one meter (near-field), transfer efficiencies more than 80% can be obtained, whereas at two meters, the efficiency is halved [180]. The WiTricity company has managed to improve the performance of the near-field WPT by using a magnetic metamaterial (MM) 'superlens', which concentrates the magnetic near fields of a source.

When long operational ranges (far-field, more than two meters) and yet high power transmission capabilities are required, microwave power transfer (MPT) is useful [179]. The MPT technology is suitable, for example, to energize lightweight mobile crafts or to transfer solar power from the Earth orbit to the Earth's surface. For high-power microwave beams, appropriately designed safety standards and regulations associated with the power density and frequency of the microwave beam are essential [181]. Firstly, the transmitter-receiver systems should be built in rural or desolate areas such as fields, open water, or unused land. Second, no-fly zones should be established to prevent objects hitting the beam. Third, the system should be equipped with appropriate emergency shut-down procedures, such as programming the beam automatically to deactivate in the event that a radar system detects an approaching object. A certain threshold time must be also set to keep the beam inactive, whereas the power demand during the shutdown is fulfilled by batteries and/or supercapacitors.

For power transfer capacity in the magnitude of micro-watts to watts, there are several further options for WPT, such as laser, radio or ultrasonic waves and resonant beam charging (RBC) [23]. Radio waves and RBC apply, for example, to biomedical applications. The technology is efficient and safe in small power and short range. The research aims at the integration of wireless power transfer and wireless communications. The integrated solution is known as simultaneous wireless information and power transfer (SWIPT). Various WPT schemes and their ubiquity characteristics are shown in Table 7.

The WPT is under intense research by both research organizations and companies. The near-field WPT is commercial technology. For example, the Apple Company has introduced several applications, such as iPhone models (iPhone 8, iPhone 8 Plus, and iPhone X), the Mophie wireless charging base and the Apple Watch Magnetic Charging Deck. Instead, the far-field WPT is still in its infancy. The development is focusing on applications within the operational range of less than five (5) meters. Simic et al. propose resonance coupling as a solution to energize Unmanned Air Vehicles (UAV) by the electromagnetic field of the power lines they are inspecting [22]. The functionality of their concept has been verified in laboratory, but it needs yet to be scaled up to the real-life applications. Using the inductive coupling scheme, efficiencies up to 90% have been reported in electric vehicle (EV) charging applications [182].

An Israeli startup company Wi-Charge has presented a wireless charging of wearable technology and household appliances using infrared laser technology. The infrared wavelength is inherently safe under normal use since its energy density is low. Moreover, Wi-Charge has presented an 'external cavity design', which makes the system stop the amplification and reduce the power transfer, when the laser hits an obstacle. The WPT system by Wi-Charge has been received the regulatory safety approval for commerce in 2018 by the USFDA (United States Food and Drug Administration). The laser WPT technology can be scaled up to the power transfer capacity of kilowatts, but in that case, the safety issues will occur and the system must be designed and integrated by following the similar principles as the microwave WPT.

Table 7
Characteristic qualities of various WPT schemes [23,179–180,182–185].

WPT scheme	Power transmisison capacity	Range	Efficiency
Magnetic Resonance Coupling	kilowatts	meters	< 60%
Inductive Coupling	kilowatts	centimeters	< 90%
Capacitive Coupling	kilowatts	centimeters	< 80%
Radiowaves	hundreds of watts	to 100 m	< 90%
Micro-waves	kilowatts	kilometers	< 85%
Photo-electricity	milliwatts	to 100 m	< 10%
Ultrasonic	hundreds of watts	meters	< 60%
Laser	milliwatts	kilometers	< 60%
Resonant Beam Charging	hundreds of watts	to 100 m	–

The uBeam company proposes ultrasonic waves to provide power for portable devices, whereas the Energous and the Ossia companies offer the radio frequency-based (RF-based) technology for mobile device charging systems in rooms (range of up to five meters). An RF-based approach called Passive Wi-Fi is also applied by Kellogg et al. in their cell phone concept that is powered only by the energy it harvests from the surrounding radio waves [186].

The Witricity company introduces an MRC-based WPT concept suitable for EV charging. The power transmission capability of up to 11 kW and the efficiency of up to 93% are claimed. The company has also concluded that bidirectional wireless power transmission for vehicle-to-grid (V2G/G2V) applications can be obtained at high efficiency (> 90%).

The start-up company Magment proposes an inductive charging of electric vehicles by the concept 'magnetizable concrete'. Their solution can be integrated in a roadway using tiles with an embedded electrical conductor is embedded. According to the company, an efficiency of 95% can be achieved at a distance of 20 cm.

3.4.2. *Off-grid and micro-grid solutions*

Preventing interruptions in power supply and promoting the whole system's recovery from failures (resilience) in all imaginable conditions and by all available means is one of the requirements appointed for the energy supply chain in the context of 'ubiquitous energy'. For example, the locally integrated energy supply chains have to enable a stand-alone operation (island mode), without a connection to national energy supply chains (grids). Yet they have to be able to work as a part of the whole system. These requirements presume that the local energy system is identified as a distinct section from the rest of the system, whereas its resources are controlled and protected in concert with each other rather than with distant resources [187,188].

The local energy systems fulfilling the above conditions are described in the Radical Technology Inquirer (RTI) as off-grid and micro-grid (also referred to as nano- or pico-grid) solutions, i.e. physical energy supply chains that contain power generation from distributed renewable energy resources (e.g. wind, hydro, solar PV and micro-cogeneration plants) and local energy storages. In addition to energy conversion and storage technologies, power electronics and appropriate control systems are included in an off-grid or micro-grid solution. Micro-grids can be (partly) direct current (DC) grids [189].

Off-grid and micro-grid solutions are primarily proposed for the applications of the scale of single buildings or neighborhoods (several buildings of various types), but the infrastructure in itself can be scaled up to the level of cities and downscaled to the level of vehicles [190]. Particularly, the micro-grid and off-grid solutions are expected to be viable in countries plagued by long distances.

In Western Australia and Queensland, the power demand may occur some 1000 km away from the nearest generation. Siemens Australia has planned a 50 MW micro-grid to supply power for up to 10,000 homes. The micro-grid would include rooftop solar PV installations of approximately 4 kW per home and an array of centralized and decentralized battery storage plus gas-powered plants, which would be later replaced by renewable fuels and/or hydrogen [191]. A micro-grid-based solution is also being planned for the Liuzhou Forest City located in Guangxi Province, China. The community of some 30,000 inhabitants is expected to be energy self-sufficient, the supply chain being based on renewable energy sources such as geothermal and solar energy [192].

Ecocapsule® is an example of a completely energy self-sufficient, off-

Table 8
Summary of SWOT qualifications of the reviewed technology portfolios from the perspective of ubiquitous energy.

Technology portfolios	Strengths	Weaknesses	Opportunities	Threats
Efficient and light solar PV/T	Enables scalable integration anywhere	Solar PV/T is an intermittent energy source, i.e. there is no access to energy any time	Accessibility to energy can be improved through integrated energy storage	Power generation (solar PV) takes place inevitably when exposed to solar irradiation
Small-scale CHP	Modular and scalable technology, allows efficient conversion from versatile heat sources to multiple types of useful energy	Limited controllability, power-to-heat ratio and operational temperatures. Sets requirements for the interface between plant and surrounding energy infrastructure	Accessibility to energy can be improved through hybridization with other energy conversion technologies and storage systems	CHP always requires a demand for multiple types of energy. If this is not the case, the overall efficiency drops dramatically due to waste energy
Harvesting of kinetic energy	Enables scalable and integrable energy recovery from any type of motion any time	Intermittent energy source with limitations in power control	Accessibility to energy can be improved through integrated energy storage and hybridization; miniaturization into nano-scale revolutionizes the integrability	Some of the application-specific challenges are not yet well-known (e.g. unpredicted noise or vibrations)
Small-scale nuclear power plants, fission and fusion	Long-term, modular energy source for base load; suitable for mass production. Nuclear fusion provides a potentially inexhaustible energy source	Waste treatment is yet a challenge	Attractive for district heating solutions; micro-scale reactors can be developed	Risk management is challenging and expensive. A potential threat may occur if a local agent does not fully commit to risk management
Rapidly charging and light energy storages	Enables the integration of scalable, high energy and power density energy storages in practically any type of material or structure	Integrability is based on materials and structures (e.g. carbon nanotubes) that are still under development	Can be integrated in wearable technology or hybridized with long-term energy storages to quicken the charging cycle. Can be built of sustainable materials	Application-specific safety issues and possible health impacts are yet somewhat unknown
Large-scale and seasonal energy storages	Enable storing large amount of energy over seasons. Necessary, when intermittent energy resources are utilized with an aim to ensure the adequacy of energy in all circumstances	Large physical size, fixed (inflexible) structure, high requirements for installation site and space, remarkable storage losses	Automation, digitalization and circular economy provide opportunities to improve the processes of design and manufacturing for large-scale energy storages	Environmental impacts and sustainability issues are yet partly unknown
Affordable hydrogen economy	Enables scalable and portable energy storage mechanism capable of providing high energy densities and negligible storage losses	Energy conversion process is complicated and its round-trip efficiency is low. There is a limited availability of hydrogen delivery infrastructure	Hydrogen may replace fossil transportation fuels. It also provides an alternative to electric batteries with significantly shorter re-fueling times	Hydrogen economy is sustainable only if the source of hydrogen is sustainable. Safety issues may pose a threat if the regulations are not followed strictly
Artificial photosynthesis and synthetic hydrocarbons	Besides the strengths of hydrogen economy, solar fuels are easy to handle and store	The solar-to-fuel efficiency is low	Provides a carbon-free and safe energy storage mechanism compatible with existing fuel delivery infrastructures	The fuel production process is not sustainable by default
Wireless power transmission	Potentially enables an access to power anywhere	Transmission efficiencies are low and the range is limited	The most promising application in short-term is wireless charging of electric vehicles and devices	Causes health impacts and raises safety issues. Some of the impacts are yet unknown
Off-grid and micro-grid solutions	A scalable, fully integrated energy system, which is independent from energy distribution grids	Challenging operational and management protocols, requires educated staff, limited resilience in failure situations	Attractive solution for isolated areas like islands and distant communities	Requires seamless communication through information networks, which exposes the system to cyber threats

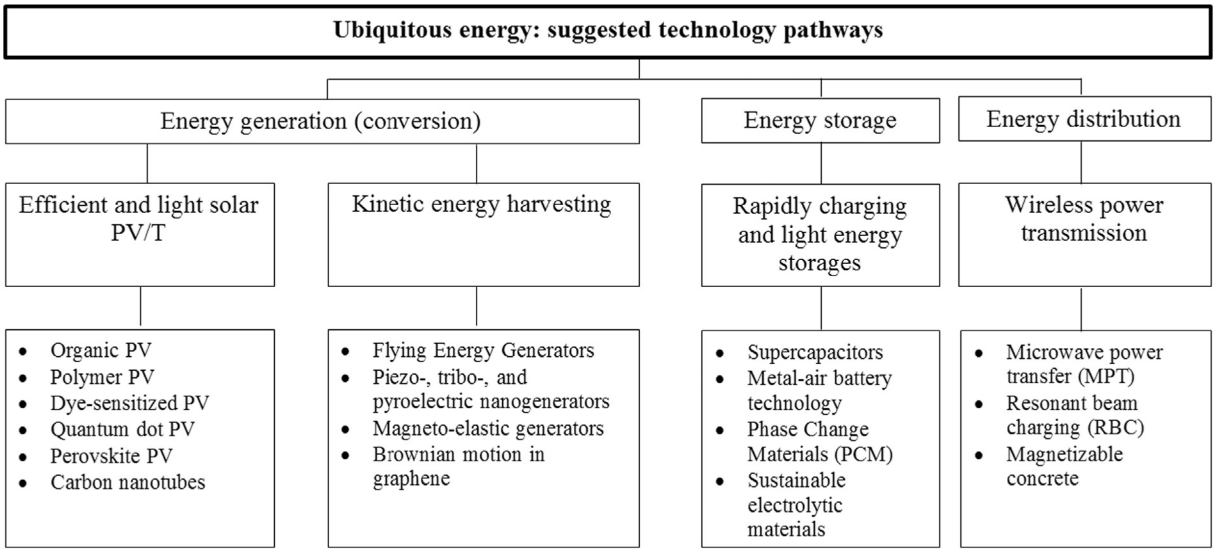


Fig. 6. Suggested technology pathways to ubiquitous energy.

grid house. The tiny cabin is with the livable area of 8 m^2 and it is powered by integrated PV panels (installed power 600 W) and a micro-wind turbine (rated power 750 W). The Ecocapsule® is also equipped with a battery (rated capacity 10 kWh). It is compatible with both 12 V/24 V DC systems and 110/230 V AC interface. There is also a possibility to use the cabin's battery for charging electrical vehicles.

The Arkup company has designed a 404 m^2 floating house capable of generating and storing the electricity required by the electric propulsion system, lighting, appliances and HVAC. The installed power of the solar PV panels is 30 kW and the covered roof area is 214 m^2. The system contains the Orca Energy Storage System (Corvus Energy), which is an approved system for marine applications. The Orca system consists of liquid or air cooled lithium ion battery modules with the capacity of 5.7 kWh per each module. The system is scalable up to the capacity of 137 kWh.

4. Summary of technology pathways

To identify the most relevant technology pathways towards related to the concept 'ubiquitous energy', we conducted a SWOT analysis, where the key strengths (S), weaknesses (W), opportunities (O) and threats (T) of the reviewed technology portfolios with respect to the qualities of ubiquitous energy are summarized. The outcome of the SWOT analysis is in Table 8.

Given that 'ubiquitous energy' presumes an access to energy anywhere and anytime, efficient and light solar PV/T, harvesting of kinetic energy, wireless power transmission and energy storage technologies at various scales are identified as the most attractive technology portfolios based on their strengths are. These technology portfolios contain the best potentialities to provide integrability, scalability and portability to realize the concept of 'ubiquitous energy' in the sense discussed in Section 3.1. Nuclear fusion is promising due to its ability to offer practically unlimited source of energy, but many of its technological challenges are still unresolved.

On the other hand, the intermittency of several renewable energy sources can be counted as a major weakness related to the accessibility to energy. Therefore, the realization of 'ubiquitous energy' requires the hybridization of scalable energy conversion and storage technologies. In applications, where the complexity of the system is not a constraint, the hybridization potentially results in a workable solution, which can be found through whole-system optimization. The low efficiency of kinetic energy harvesting and wireless power transmission is yet a significant challenge. Hence, implementing these technologies is limited to few areas of application in the short term.

The opportunities of the reviewed technology portfolios can be realized through intense research and development. Besides improving the energy efficiency and affordability, efforts should be directed to enabling the miniaturization and integration of energy conversion and storage. The solutions based on new materials, such as graphene, should be examined. On the other hand, the transition towards ubiquitous energy requires the adaptation of the prevailing energy system. Therefore, the interoperability between emerging and conventional technologies has to be ensured through standardization.

The threats listed in Table 8 are more or less associated with the maturity of technology and lessons learned through operational experience. Thus, an important research challenge before the new energy era is to examine the functionality of technology in realistic operational conditions.

Examples of the most relevant technology pathways for ubiquitous energy according to our review and analysis are provided with more detail in Fig. 6.

5. Conclusions

In this review article, we use the term 'ubiquitous energy' to provide a single, concise expression and discussion framework to describe 'pervasive energy supply chains that guarantee an access to adequate resources of energy and power for all energy users at any moment of time'. We conclude that the concept of 'ubiquitous energy' requires the classification of energy supply chains according to their scope and the degree of integration (decentralization). The concept in itself allows centralized and decentralized, as well as large-scale and small-scale solutions, whereas the most prominent trend of development is the use of distributed and shared resources, which will be mainly realized through local energy supply chains serving communities or single buildings. Here, the energy supply chain is anticipated to include networks of energy hubs (EH), where the production, conversion, storage and consumption of various energy carriers take place. Hence, the aforementioned networks are also hybrid smart grids capable of delivering multiple energy carriers and include the advanced information and energy management facilities.

Regarding the evolution of the energy supply chain towards the new energy era and 'ubiquitous energy', we conclude that the accessibility to energy can be improved by integrating mobile energy hubs (MEH) to operate together with hybrid smart grids. This approach allows the Mobile Energy Internet (MEI), defined by us as a 'hybrid smart grid, which enables the exchange of any energy type between static and mobile energy hubs'. Again, the MEI has a potential to comprehensively change the philosophy of design and operation of the communities' energy system, which, in turn, provides several research avenues regarding novel business logic, sharing economy, improving the resilience of energy systems and the utilization of local energy resources.

The second purpose of this article is to make visible the most promising technology pathways related to 'ubiquitous energy'. To that end, we have described a systematic framework to classify energy technologies under energy generation, storage, transmission and distribution according to the recent Radical Technology Inquirer (RTI) of the Committee for the Future of the Finnish Parliament. We have also analyzed the key technology portfolios using a SWOT analysis according to their contribution to 'ubiquitous energy'. To that end, we have developed an assessment framework, where the quality of 'energy to be present everywhere and any time' for each technology portfolio is evaluated against three main criteria, namely, 'adequacy', 'accessibility' and 'affordability'. These main criteria are further characterized by subcriteria such as, scalability, dispatchability and integrability.

We conclude that on one hand, the integration of energy conversion and storage technologies and on the other hand, wireless power transmission, are essential. Particularly, efficient and light solar PV and battery energy storage technologies are currently under an intense research. However, pursuing the conditions of 'ubiquitous energy' requires more research on the integration and hybridization of the variety of energy conversion and storage methods in different scales. More research should be also focused on wireless power transmission (WPT). Specifically, the challenge is to improve the transmission efficiency and safety within the long range. Again, the opportunities to integrate new technology in both existing and developing infrastructures should be investigated. For example, the accessibility to energy to distant areas in developing countries should be encouraged.

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