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Sustainable wireless power transfer in the context of one health environmental approach

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Abstract

The everyday well-being of contemporary humanity is intimately linked to the utilization of different devices functioning using different sources of energy conversion. The practice of these devices exhibits expected outcomes, which are often associated with unwanted side effects. The present contribution aims to analyze the significance of the approaches of Reliable Attitude, corresponding to eco-design and optimization, and One Health, related to global biodiversity, in the managing of the daily usage of electromagnetic energy wireless transfer devices. The pursued analyses in the paper are supported by a literature review.

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Introduction

In an up-to-date society, different appliances are exploited for the daily well-being of humans involving health, safety, comfort, etc. These apparatuses function using diverse sources of energy conversion. Such tools, along with offering their intentional conveniences, yield unwanted side effects. A continuous aim has at all times, been to optimize the practice of these means. Thus consolidating the projected outcomes and minimizing unsolicited side effects that might disturb not only individuals but also other connected environmental involvements. These hostile influences principally disturb human health along with that of animals, plants, and largely biodiversity. Thus appealing to the One Health concept that comprises human, animal, and plant health, all menaced by disruptions engendered by human activity[1].

In addition, energy and environmental sustainability that represents one of the common defies targeting to guarantee a supply of clean energy for the well-being of humans. The managing of well-being and troubles associated with the employment of a manmade appliance are ruled by a concept of Reliable Attitude in the conversion and utilization of such clean energy. These two approaches applying One Health (OH) and Reliable Attitude (RA) would permit optimized consumption of energy impending human well-being with reduced unsafe side effects on humans, and biodiversity.

Among the devices operating with clean energies linked to human well-being, wireless electromagnetic energy tools occupy an important place. These are mainly wireless power transfer devices and daily communication tools. These appliances, besides their actual roles, like numerous mechanisms, have their specific side effects. Thus, they play like unexpected sources of electromagnetic fields (EMF) radiated fields. These are related to the wireless feature, which results in stray and leakage fields. Their influence is focused on the radiated object at a contiguous range, e.g. cell phone or wireless energy transfer device[2−5], and uniform in distant exposure, e.g. cell phone tower antenna[6].

Considering wireless power transfer (WPT) devices, they involve mainly four categories related to the employed transfer technology namely magnetic, electric, microwave, and laser[7]. The differences in such technologies are mainly related, in addition to the used transfer technique, to different factors. These are the transferred energy range, the transmission distance, as well as performance, sensitivity, limitations, and complexity. The various WPT applications are directly correlated to these mentioned factors.

In magnetic (WPT) also called inductive power transfer (IPT) devices, two notions rule their functioning, the Ampère's law (1820) and Faraday's magnetic induction principle (1831). These basics posterior assisted Nikola Tesla (1856–1943) to present WPT in the 1890s[8−10]. WPT devices were first founded to transmit energy over long distances using microwave rays[11,12]. Similarly, the notion of WPT projects electric power production in space of solar energy, over satellites of solar-power and microwave power diffusion for consumption on the globe[13,14]. It is only lately that close-range near-field inductive WPT (IPT) equipment has been extensively utilized for battery charging of various daily tools such as cell phones, domestic articles, drones, and electric vehicles[15−26]. IPT or WPT denotes the contactless transfer of energy from a power source to a load from side to side of an air gap. An IPT scheme involves two coils, a transmitter and a receiver.

Wireless power transfer (WPT) technology is an important topic of actual investigation in electrical engineering sciences in general. Potential utilizations enclose a wide variety of areas, including mobility, power generation, charging, biomedical, etc.[27−33]. The justifications for such a varied set of uses are also numerous and different. For example in some medical implants, sensing devices, and pacemakers, WPT advances secure charging deprived of any physical contact or the need to work under surgery. Additionally, in many industrial projects, the need for contactless power transmission for moving loads overcoming complications related to slippery contacts or moving power cords stimulated the development of contactless energy transfer (CET) links[34−36].

This contribution targets to analyze and illustrate the behaviors of WPT devices in the background of the OH approach involving biodiversity and the RA concept involving optimized management of clean energy. The investigation is part of a current context where wireless technology is increasingly used for energy transfer, in particular through, the use of autonomous systems and the utilization of carbon-free energies. A typical example of a carbon-free autonomous application is related to the replacement of combustion engine vehicles with electric vehicles equipped with electrical energy storage batteries. This solution was programmed within an ecological framework of reducing air pollution and protecting the planet biodiversity, which have become crucial today. These vehicles will eventually operate with wireless charging of their batteries when stationary or running. By replacing means of transport that have become dangerous for biodiversity, we must ensure that the new solution will protect this biodiversity. Additionally, the manufacturing of wireless power transfer batteries chargers of these vehicles must reflect optimal clean energy-saving ecology. It is in this context that the two concepts of One Heath and Responsible Attitude find their place in the design and control of WPT tools.

The different analyses performed in the paper are based on magnetic WPT (IPT) but the context is still valid for WPT in general; the term WPT will denote in analyses an IPT. In the following sections, the management of WPT with optimized consumption of energy and impending human well-being with reduced unsafe side effects for humans, and biodiversity will be first presented. Then living tissue biological effects due to exposure to EMF radiated by WPT devices will be analyzed. The governing phenomena and their mathematical representations of the conduct of such effects will then be reported. Subsequently, procedures for safeguarding against the unsafe consequences of EMF exposure will be examined.

Sustainable RA optimization of WPT

Such optimization involves behaviors related to the input (grid), output (load), and their ratio (efficiency). These affect the expected outcome (human well-being), the EMF stray exposure (human and biodiversity unsafety) the power factor, and the different losses (grid and environmental sustainability). Figure 1 illustrates a summarized schematic illustration of a WPT coupler composed of the primary (transmitter) and secondary (receiver) coils (with inductances of L_1 and L_2) separated by their airgap (reflecting a mutual inductance M_{12}). Each of the two sides of the coupler is compensated (by capacities C_1 and C_2). These two functions, energy transfer, and capacitive compensation, feature the operation of the WPT device. Actually, the first function related to the inductive coupler transformer (ICT), allows wireless transfer using the magnetic induction guaranteeing a galvanic separation of the source and the load. The second function related to the capacitive compensations permits the power of electronics linked to ICT to operate at a resonance that optimizes the procedure. These power electronics are involved in the two conversion stages connecting the ICT to the source and the load. The airgap size of ICT is relatively important and so the coupling of the two coils is weak. Thus, to reach the required transmitted power, a significant reactive power should be absorbed, so the use of resonant components (capacities)[22–25,37–44] in both sides of the ICT are indispensable for compensation to guarantee good efficiency. Several compensation topologies of reactive power are established on the necessity of the receiver load such as SS, SP, PS, PP, etc.[22,38]. The SS (Series-Series) compensation one is an economical option[22,44]. Maximizing the power transfer efficiency is generally realized through magnetic ferrite sheets covering the two ICT coils. The improvement of WPT is related to better coupling coefficient k according to $k = M_{12} \times (L_1 \times L_2)^{-1/2}$. The two resonant circuits for SS compensation of the transmitter and receiver are tuned at the resonant frequency $\omega_o = (L_1 \times C_1)^{-1/2} = (L_2 \times C_2)^{-1/2}$.

These conversion features are dependent of WPT application, fixed or portable, source and load natures, power range, etc. Figure 2 represents a summarized schematic illustration of an example of a static WPT for charging of battery load from the grid. The ICT is inserted between, the input grid through a converter-filter-inverter (frequency-controlled), and the load through a converter-filter. The input conversion stage, involving grid frequency converter, filter, and high-adjusted frequency inverter, permits the power adjusting by monitoring the ICT input voltage and frequency.

The RA sustainable optimization of the WPT could be achieved through the design of the ICT structure (coils and ferrites), the compensation elements, the different static convertors and filters. Such optimization involves losses reduction (higher efficiency), better power factor, improved coupling and reduced stray field radiation. The details of optimization of WPT, are not in the focus of the present contribution and could be found for enhanced performance in[37–45] and reduced unwanted EMF effects for humans and biodiversity[46–48].

Living tissues biological effects due to WPT EMF exposure

EMF exposure or radiation settles an interaction of EMF with an exposed substance occasioning a dissipation of electromagnetic energy in it. Such dissipation yields diverse effects in the material connected generally to EMF frequency range.

EMF waves exhibit widespread frequency range covering non-ionizing (10^3–10^{14} Hz) and ionizing (10^{15}–10^{22} Hz) spans. The non-ionizing ones are those consumed in quotidian human accomplishments like WPT devices. The most popular effect of such exposure in particular in the range (10^5–10^{14} Hz) that involve most WPT applications, is a temperature rise contingent to the characteristics of exposure and the menaced substance. The radiation attributes comprise the field strength, frequency, nature, and the interval of exposure. Those of substance relate to its physical assets comprising electric, dielectric, magnetic, heat, and mechanic incidents. This common thermal effect generally occurs for reduced radiation (due to shielding), reasonable exposure time (relatively short), and distance (relatively far) from the source. It should be noted that disproportionate field potencies, frequencies or duration could trigger irreversible molecular disturbance that can stimulate nerves, muscles, and excitable structures.

In the case of living tissues, the biological effects (BE) of EMF emitted by WPT devices are commonly, as mentioned before, thermal effects after to energy dissipation in tissues. These affect the tissues of humans, fauna, and flora. In these cases, an instantaneous BE due to high-frequency field exposure would increase internal tissue temperature. The natural resistance to heating of these living tissues is mainly adapted to superficial heating of the material such as exposure to the sun. In this case, heat is gradually diffused by conduction and convection inside the tissues usually irrigated by fluids allowing them to function correctly. Conversely, concentrated heating inside the tissues, particularly in tissues poorly perfused or unwell irrigated by blood or sap, under EMF radiation, could be dangerous depending on the characteristics of the exposure and the tissues; see e.g.[47,48]. Different harmful effects of WPT radiated EMFs could be verified by assessment relative to thresholds fixed by standards considering the nature of tissues, the exposure functional and conditions; see for human and fauna[49–51] and for plants[52,53]. Concerning the frequency effect, it should be noted that low

Fig. 1 Schematics of a compensated ICT in a WPT device.

Fig. 2 Example of a static WPT for charging a battery from an AC grid.

frequencies are used for near-field applications like IPT for electric vehicles and high frequencies for far-field applications like WPT MW devices to transmit power through free space in the form of waves. Both involve EMF radiation but with different biological effects. In fact, the higher the field strength and frequency, the more severe the effect will be due to the deeper effects on internal tissues as mentioned earlier. Of course, adjusting the frequency can reduce the effects of radiation, but will degrade the tool's performance.

Governing phenomena and equations related to WPT exposure

The implicated phenomena in unsolicited thermal BE due to the interaction of EMF emitted by WPT with matters are the electromagnetic (EM) coupled with heat transfer (HT) phenomena. The coupling of these phenomena will be through the power dissipated in the matters. In the case of living tissues, the interaction with EMF will comprise an increased heat transfer occurrence that is a bioheat (BH) phenomenon. The temperature rise in the tissue will be determined by the BH phenomenon initiated by a source consistent with the EM dissipated power in the tissue, which can be determined by the EM phenomenon due to exposure. Thus, the EMF and BH equations govern thermal unwanted BEs due to EMF exposure.

EMF equations

The general EMF four equations, in their differential form, based on Maxwell's microscopic local equations[54] are given by $\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$ (Maxwell – Faraday), $\nabla \times \mathbf{H} = \sigma \mathbf{E} + \partial_t \mathbf{D}$ (Maxwell – Ampère), $\nabla \cdot \mathbf{D} = \rho e$ (Maxwell – Gauss), and $\nabla \cdot \mathbf{B} = 0$ (Maxwell – Thomson).

In the case of harmonic fields, the EMF equations can be given by:

$$\nabla \times \mathbf{H} = \mathbf{J} \tag{1}$$

$$\mathbf{J} = \mathbf{J_e} + \sigma \mathbf{E} + j\omega \mathbf{D} \tag{2}$$

$$\mathbf{E} = -\nabla \mathrm{V} - j\omega \mathbf{A} \tag{3}$$

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{4}$$

In the above EMF equations, **H** and **E** are the vectors of the magnetic and electric fields in A/m and V/m, **B** and **D** are the vectors of the magnetic and electric inductions in T and C/m^2, **A** and V are the magnetic vector and electric scalar potentials in W/m and volt. **J** and $\mathbf{J_e}$ are the vectors of the total and source current densities in A/m^2, σ is the electric conductivity in S/m, ρ_e is the volume density of electric charges in C/m^3, and ω is the angular frequency = 2πf, f is the frequency in Hz of the exciting EMF. The symbol ∇ is a vector of the partial derivative operators. The symbol ∂_t is the operator of the partial time derivative. The magnetic and electric comportment laws respectively between **B/H** and **D/E** are represented by the permeability μ and the permittivity ε in H/m and F/m.

The source term in the EMF Eqns (1) – (4) is the excitation current density $\mathbf{J_e} = \sigma \mathbf{E_e} = j\omega \mathbf{D_e} = j\omega\varepsilon \mathbf{E_e}$. The volume density of the dissipated power P_d in dielectric materials (biological tissues) and the corresponding specific absorption rate (SAR) are given by:

$$\mathrm{P_d} = \omega \cdot \varepsilon'' \cdot \mathrm{E}^2/2 \tag{5}$$

$$\mathrm{SAR} = \mathrm{P_d}/\rho = \omega \cdot \varepsilon'' \cdot \mathrm{E}^2/(2\rho) \tag{6}$$

In Eqns (5) and (6), parameter: ε'' is the imaginary part of the complex permittivity of the absorbing material and ρ is the material density in kg/m^3. E is the absolute peak value of the electric field strength in V/m and SAR is in W/kg. The power dissipation in W/m^3 given by Eqn (5) relates to the foremost dielectric heating of EMF energy loss. Notice that the imaginary part ε'' of the (frequency-dependent) permittivity ε is a measure for the ability of a dielectric material to convert EMF energy into heat. The volume density of power dissipations given by Eqn (5) will be used in the coupling of EMF and BH equations.

BH equation

The HT equation in its differential form is given by:

$$\mathrm{c}\,\rho \partial \mathrm{T}/\partial \mathrm{t} = \nabla \cdot (\mathrm{k} \nabla \mathrm{T}) \tag{7}$$

In Eqn (7), c is the specific heat of the substance in J/(kg °C), ρ is the density in kg/m^3, k is thermal conductivity in W/ (m·°C), and T is the substance temperature in °C.

Considering the case of living tissues, we have to consider in Eqn (7) a self-tissue heat source P_t and the involved convective heat transfer *via* irrigating fluid of tissue. On the other hand, we have to consider in Eqn (7) the external heat source related to the EMF exposure, P_d is given by Eqn (5). Under these conditions, Eqn (7) will be extended to a tissue BH equation, which can be presented as follows:

$$\mathrm{c}\,\rho \partial \mathrm{T}/\partial \mathrm{t} = \nabla \cdot (\mathrm{k} \nabla \mathrm{T}) + \mathrm{P_d} + \mathrm{P_t} + \mathrm{c_f} \rho_\mathrm{f} \mathrm{p_f} (\mathrm{T_f} - \mathrm{T}) \tag{8}$$

In Eqn (8), P_t and P_d are heat sources in W/m^3, T_f and T are respectively the fluid temperature and the local temperature of tissue in °C, and c_f, ρ_f, p_f are respectively fluid, specific heat in J/(kg °C), density in kg/m^3, perfusion rate in 1/s.

Equation (8) relates to bio-heat tissues considering the EMF exposure. This equation has a similar form as Penne's bio-heat equation[55–58] associated with human living tissues involving convective heat transfer in blood fluid. Plant sap fluid plays the role of blood in animals. Moreover, phloems and xylems containing sap play the role of arteries and veins inclosing blood. Note that in Penne's bio-heat equation the term P_t in Eqn (8) is related to living tissues' metabolic heat and corresponds to plant tissues' internal heat. As well, the last term in Eqn (8) representing convection fluid heat transfer corresponds to animal blood or plant sap.

Coupled solution of EMF and BH equations

Equations (1)–(4) and (8) can be solved in a coupled manner. Because of the geometric complexity and inhomogeneity of tissue, the solution should be local in the tissue using discretized 3D techniques as finite elements[59–67] in the tissue. The coupling of the EMF and BH equations is weak due to the distant values of their time constants[55–57]. Thus, performing an iterative solution offers in the tissue the local distributions of the induced values of the fields $\mathbf{E_i}$, $\mathbf{B_i}$, and $\mathbf{J_i}$, and hence P_{di}, SAR_i, and ΔT_i. The involved parameters are those related to the assets of tissues, ε, P_t, c_f, ρ_f, p_f, etc. These could be found in literature or measured[68–71].

OH protection of WPT field radiation

As mentioned previously, the optimization of a WPT system aims to consolidate the projected energy transfer and reduce unsolicited EMF radiation that could disrupt not only individuals but also any other connected environmental biodiversity. Such objectives could be achieved through optimization of the design and monitoring of the WPT. Concerning the protection against far radiation (target not close to the ICT), different shields can be used. Reducing near EMF (target close to ICT) disturbances is a tedious task, especially in the case of sources related to wireless devices. In fact, for conventional sources emitting electromagnetic fields, target protection could be achieved *via* shielding the source, the target, or both. Note that source shielding is generally not suitable for wireless sources as WPT because the operating principle of a wireless device is linked to its emitted field. This effect is stronger for larger or twisted coil airgaps.

Considering the above and in the context of the OH concept which encompasses human, animal, and plant health, all threatened by disturbances caused by human activity, only mitigation protection strategies could be used. Thus, the use of WPT devices reflecting near-target EMF exposure could be associated with restricted time intervals or areas of use[72–74].

This protection option focuses principally on anthropogenic developments and their associates with the environment and biodiversity, thus revealing the OH approach[1]. Note that there is a less effective technique than shielding for reducing EMF radiation for large fields, but they could still be used advantageously for small sources with moderate fields, which could be the use of field absorbers[75,76] or the use of certain types of ornamental plants such as the snake plant[77,78].

Interconnection of RA and OH approaches

The present manuscript concentrated on the approach of RA via the optimized design and use of clean energy WPT and the concept of OH by considering the whole biodiversity involving humans, animals, and plants in the management of adverse EMF exposure effects including evaluation and protection related to such effects. Indeed, the different analyses of WPT means reported in the different sections of the paper could be divided in two interconnected activities. The optimization of artificial WPT devices using electromagnetic clean energy dedicated to enhanced performance and minimized BE for biodiversity security; thus, such eco–design, and protection belong to RA concept. In the second activity, the biodiversity safety evaluation and protection included living tissues of humansandthisenvironmentalecosystembelongstotheOHapproach. Figure 3 shows a summarized schematic illustration of the interaction of these two activities in the management of a WPT device.

Discussion and conclusions

In the sections above, the following analyses were devoted to magnetic WPT, which are IPT devices as indicated in the introduction. In the context of RA and OH, such analyses apply to WPT in general, as mentioned previously. WPT mainly involves four categories related to the transfer technology used namely magnetic, electric, microwave and laser.

In this section, the main characteristics of principal categories of WPT devices will be summarized and ending with a summary and recommendations for this contribution.

Conferring basic categories of WPT

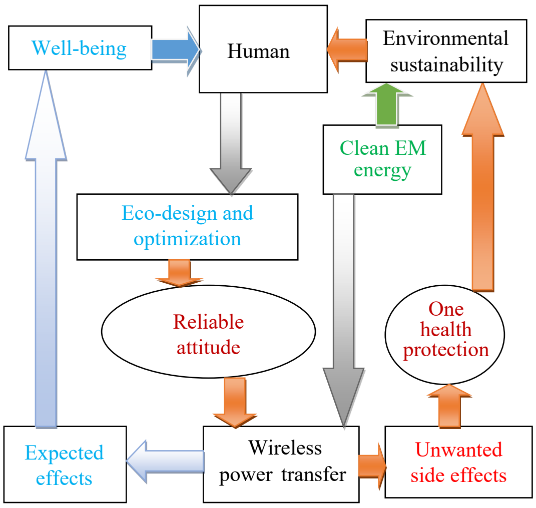

Fig. 3 Summarized management of RA and OH concepts in clean energy WPT with enhanced performance and protection anti adverse living tissues BE.

Magnetic

WPT, which is an IPT, uses static energy converters to transfer energy through loosely coupled coils operating in resonance mode. Such a simple structure can transmit high powers with high efficiency. Due to its simple configuration and high security, IPT is involved in various applications, e.g. wearable devices, underwater robotics, and transportation. It suffers from a narrow transfer range, sensitivity to coils relative placement, and likely risk of interaction with other objects, including living tissue[79–81].

Electric

WPT reflects economical design, low weight, and slimness. It transfers energy *via* high- frequency electric fields to reduce the effects of metal barriers. It is used in small transfer range applications lik medical tools and daily electronics. However, the low dielectric constant of air limits its power, requiring advancements in wide bandgap devices[80,82,83].

Microwave (MW)

WPT devices transmit energy through free space in the form of waves, which suffer losses mainly due to atmospheric circumstances, obstacles, dust, etc. It reflects precise control of MW beam strength and orientation, enabling applications in space solar power plants, and high-altitude craft, which correspond to long-distance transmission with low losses. However, cost and complexity limit its common use[84–86].

Laser

WPT uses laser energy transmission, which allows high-energy orientation and concentration, making it suitable for unmanned aerial vehicles, solar power plants, and underwater devices. It suffers from dependence on environmental conditions and possible health risks of lasers[87–89].

Contribution condensation and recommendations

This contribution demonstrated that the optimized construction and use of WPT using clean electromagnetic energy (obtained by conversion of a clean form of energy) allows the expected performance of devices and takes into account the involved biodiversity in the management of harmful biological effects. In this framework, the estimation of harmful biological effects, due to exposure to WPT electromagnetic fields, in living tissues of biodiversity as well as their reduction *via* a protection routine have been reported and analyzed. This showed that the concepts of Reliable Attitude and One Health reveal interconnected activities in this usage. The analyses carried out on the basis of the magnetic WPT (IPT), clearly justifies such concepts considering the mentioned context of the example of the replacement of combustion engine vehicles by electric vehicles equipped with electric energy storage batteries. Indeed, the optimization of the IPT and the control of its effects on the field exposure, guarantee eco-design and overall protection of biodiversity. Such protection could be enhanced using target shields for far-field exposures and restricted usage time intervals or/and restricted radiation-free zones for near-field exposures.

Author contributions

The author confirms sole responsibility for the following: study conception and design, draft manuscript preparation, and the final version of the manuscript approval.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The author declares that there is no conflict of interest.

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