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Graphene-Based Materials for Energy Harvesting at Microwave Frequencies: A Comprehensive Review

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ABSTRACT

Harvesting energy from microwave frequency is one of the key areas of research in the past decade to provide an alternative power source for wireless devices and sensor networks. The increase in the employment of Internet of Things (IoT) devices as well as sensors in order to support technological advancement leads to an increase in the energy demand. This in turn leads to environmental pollution due to the large amount of batteries being disposed. As such, in order to support the current demand for clean and sustainable energy that can reduce environmental pollution, various approaches to reduce the usage of conventional batteries in these systems are being researched. One of the approaches is the usage of the antenna to harvest radio frequency energy. The appearance of graphene-based material further sparked the interest of researchers due to its exciting properties. Therefore, this paper aims to provide a comprehensive review on the advancement of the usage of graphene-based material in the field of harvesting ambient radio frequency energy. Graphene material is first introduced in order to understand its characteristics and properties as a replacement for the conventional copper material. Current state-of-the-art approaches on graphene-based radio frequency energy harvesting systems were then reviewed and compared. The future prospect of graphene-based material in energy harvesting systems was also presented and discussed, shedding light on the future potential areas for research and development.

Keywords: Microwave Frequencies Energy Harvesting; Energy Harvesting; Graphene-based Material

INTRODUCTION

Over the past decade, advancement in technology, conceptualized by the fourth industrial revolution (4IR), have led to rapid development of wireless systems such as wearable electronics and Internet of Things (IoT) (Bai et al. 2020). As widespread deployment of sensors, which are often deployed in remote places, are needed to meet the requirement of these wireless systems (Carbajales et al. 2015). These wireless sensor networks are normally powered by batteries which results in severe pollution of the environment during the disposal of these batteries. Furthermore, the need to replace and dispose of the used batteries proved to be a hassle (Chen et al. 2014). Therefore, there is a need for an alternative method to provide power to these wireless sensor networks which is environmentally friendly and long lasting. One such alternative is the usage of natural energy such as harvesting energy, where energy from external sources is provided to small, wireless autonomous devices by deriving, capturing and storing these harvested energies (Tan et al. 2022). Examples of natural energy sources, also known as ambient energy, that could be harvested are thermal energy, solar power, wind energy, mechanical energy and salinity gradients (Tentzeris et al. 2014). All of this energy can be converted into beneficial DC power (Chao K.C. et al. 2014). Harvesting of ambient energy provides several advantages such as improving efficiency of devices and systems, enabling implementation of new technologies such as 5G network for digital healthcare (Kang et al. 2023) and reducing cost of fabrication. Besides the forementioned ambient energy sources, radio frequency energy harvesting is currently one of the emerging technologies that have the potential to power the next upcoming generation of wireless sensor networks by excluding the need of batteries as the power source. It is transmitted continually for 24 hours using a different transmitter (Kang et al. 2016). Radio frequency (RF) energy harvesting provides the possibility of endlessly powering these wireless sensor networks while being environmentally-friendly (Chang et al. 2022). Besides that, it is available everywhere and anytime (Kang et al. 2016). Figure 1 illustrates the block diagram of an effective antenna network which includes a RF signal to direct current (DC) conversion circuit (Nornikman et al. 2018). The impedance of the antenna as well as the energy conversion circuit are the main parameters that affects the efficiency of the antenna (Devi et al. 2011, Devi et al. 2014). Conventional RF energy harvesting systems comprises of antenna, voltage booster rectifier, impedance matching circuit and charging circuit where antenna is the main component of the system.

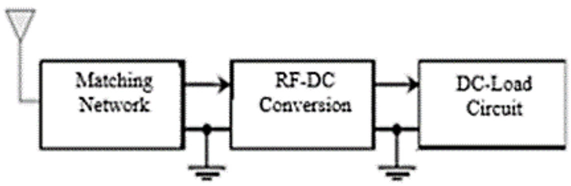

FIGURE 1. Antenna network with RF to DC conversion circuit.
Source: Nornikman et al. (2018)

Among the multiple ways to improve the performance of the antenna, graphene was one the ones that stood out and triggered intense research efforts due to its outstanding properties. Graphene is a two-dimensional carbon material with a honeycomb lattice carbon atom structure caused by the hexagon manner atom bonding (Geim et al. 2011). Discovery of graphene material in (Novoselov et al. 2004) led to numerous research curiosity in different fields due to its distinctive characteristics. Unlike conventional materials such as silicon, graphene displayed outstanding properties in electrical and thermal conductivity (5000 Wm-1K-1), electron mobility (200000 cm2V-1s-1), mechanical strength (130 GPa), zero band gap, flexibility and outstanding biocompatibility (Akbari et al. 2014, Larciprete et al. 2011). The material was also superior in weight, cost and environmentally friendliness when compared to the conventional metal used in antenna, copper. Further exploration of advanced methods in the synthesis of graphene, for example, chemical vapor deposition (CVD) further increased research interest on the material for radio frequency energy harvesting on the THz frequency range. Plasmonic responses which appeared in graphene at terahertz and infrared frequencies further piqued the interest on the usage of graphene for terahertz transmitters and receivers as well as antenna integrated optoelectronics (Yoon et al. 2011). Due to graphene's outstanding properties, the material was considered to be an excellent replacement to the copper metal to be used in antennas. Graphene material can be deposited onto various kinds of substrates including textile and paper (Prauzek et al. 2018, Perruisseau Carrier, 2012). However, it is worth to note that to date, most researches done on graphene-based antennas are proposed and scrutinized hypothetically with the response of the antenna being evaluated with the help of simulators using numerical solvers. As such, in order to meet the demands of the antennas for energy harvesting usage, further exploration on the usage of graphene-based material for the harvesting of ambient energy still needs to be conducted.

This review paper aims to provide a provide a systematic review on the research conducted on graphene-based material in the field of energy harvesting at microwave frequencies. In Section 2, various recent advancements on graphene-based material energy harvesting were explained and discussed. Section 3 discusses on the future developments regarding graphene-based material for the energy harvesting of microwave frequencies. Section 4 draws some conclusion and perspectives on the topic.

GRAPHENE-BASED MATERIAL IN ENERGY HARVESTING AT MICROWAVE FREQUENCIES

Graphene-based material are often used as a substitute for copper material in antenna which acts as the core for the energy harvesting system. Screen-printing method is one of the more popular methods used to deposit graphene material onto the antenna.

(Ram et al. 2021) designed and tested screen-printed graphene antenna on flexible substrates in the field of wireless energy harvesting applications. The novelty of the study was the customization of graphene-based antenna for the application at 2.45 GHz where the antenna in the rectenna mechanism functions as a front-end receiver. The antenna was designed as a defective ground structured circular patch antenna as shown in Figure 2 using screen printing technique while the flexible substrates such as polyester and wax-coated paper. Results based on simulations using COMSOL Multiphysics and finite element method (FEM) based Multiphysics simulation package were analyzed and used for the optimization of the antenna design. The graphene ink used in the screen-printing process is customized by suitable material analysis techniques. Graphene ink was fabricated by mixing suitable bonding material with the low-density graphene powder in a 3:2 ratio to ensure the viscosity of the graphene ink during screen-printing process. The graphene-based antenna performance was then tested by using a Vector Network Analyzer. Results proves that the fabricated flexible antenna can contour to the body surface without affecting the radiation pattern and showed potential in acting as an ultra-wideband antenna. The graphene antenna was also considered to function as a rectenna due to the it's high gain properties. The rectenna setup proves the potential of the flexible antenna prototype being used to harvest energy from radio frequency signals as the prototype have the ability to harvest energy at a range beyond 2.25m in the case that the range of transmission is high enough.

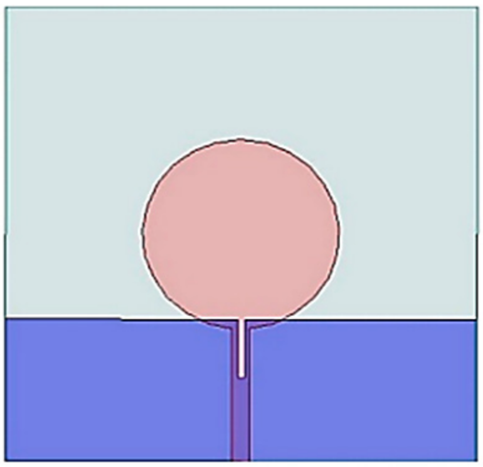

FIGURE 2. Defective ground structure circular patch antenna

Dragoman (2016) proposed the efficient energy harvesting of electromagnetic energy at terahertz frequency with the usage of graphene rectenna. The proposed graphene rectenna consists of a monolayer graphene bow-tie antenna on substrates such as n-type GaAs substrate and n-type Si substrate. The antenna structure was used because of the antenna's intrinsic properties such as low-profile, high radiation efficiency and the ability to form oxide layer between the arms' gap. The high mobility of monolayer graphene causes a Schottky barrier to form at the graphene-semiconductor interface when the monolayer graphene was transferred onto n-doped Si and GaAs substrate. The proposed design ensures that the antenna functions as the rectifying diode at the same time while exploiting larger surface area which increases the Schottky diode total current. The system was simulated and linearly characterized using Computer Simulation Technology (CST) Microwave Studio and the outputs were used to for the customized nonlinear simulator where the proposed system's rectification capabilities unified electromagnetic/nonlinear estimations were provided. Results indicates that the graphene bow-tie have a lower computed radiation efficiency when compared to the Au/Ti bow-tie. However, the Au/Ti bowtie showed significantly worse performance in rectification capabilities. The graphene bow-tie with a n-GaAs substrate have a more homogeneous radiation pattern at all frequencies of interest. The graphene bow-tie with n-Si substrate showed even lower radiation efficiency but the radiated electromagnetic field exhibits good reflection properties. The THz energy harvesting system was composed of a Schottky diode and a bow-tie antenna which gives the system the ability to limit the impedance mismatch of the antenna-diode. As such, the issue of the low conversion efficiency of the THz harvesters which occurs due to the separate metallic antenna and diode can be solved.

A multilayer screen-printed flexible graphene antenna to be applied in the field of industrial, scientific and medical (ISM) band and energy harvesting was proposed (Ram et al. 2021). Paper and polystyrene were used in the study as flexible substrate to ensure the cost and availability of the materials used. The multilayer printing technique helps enhance the properties of the graphene layer, improve conductivity and provides a smoother surface ensuring the radiating patch exhibits a uniform flow of power. The study used a notch included defective ground structure microstrip circular patch antenna. As such, the antenna is structured similar to that of a disc monopole antenna due to the defective ground structure and notch inclusion. The reduction of the ground plane enables a wider band of operation yielding a wide band antenna. The notch inclusion enables the antenna to obtain a moderate bandwidth as thin flexible substrates usually have a narrower bandwidth. The antenna design is simulated in Ansys HFSS to optimize in order to obtain the desired frequency of 2.45 GHz. In order to avoid porous formation, graphene ink with a viscosity of 4.2 to 4.7 cP was prepared by combining suitable bonding material with low density graphene powder in a 3:2 ratio. Comparing both substrates, the graphene surface on polystyrene substrate is smoother due to the substrate's lower absorption ability and smoothened surface. The antenna parameters of the paper substrate show better results compared to the polystyrene substrate except for the gain of the antenna. With the increase in graphene layers printed on paper substrate, parameters such as voltage standing wave ratio (VSWR), return loss and gain also gradually increases. The polystyrene substrate, on the other hand, shows degrading in performance during the second layer while the third layer improves the performance which is 3.6% lower than the first layer. The difference in the performance of the substrates during multilayer printing is because of the different absorption ability and surface smoothness of the substrates. The radiation patterns of both substrates remain similar throughout the multilayer printing

(Masotti et al. 2014) proposed the harvesting of energy in the far infrared frequency band by utilizing a graphene-based nano-rectenna. The proposed realistic nano-rectenna have the ability to harvest human heat. The THz rectenna implementation was unquestionably hampered by the lack of rectifying diodes in that frequency band. Even the commonly used tunnel Metal-Oxide-Metal (MOM) diode exhibited poor rectification performance in the THz-DC conversion. The introduction of the first diode on graphene in the study tried to bridge the gap and was successful in rectifying up to 30 THz of insulation resistance (IR) power. The study experimented on two different rectenna architectures which are multi antenna-multi rectifier solution and single array-single rectifier solution. The single array-single rectifier approach in known direction of arrival (DOA) signals where diode losses are maintained at a minimum. The multi antenna-multi rectifier approach losses array-factor, which showed better performance when the DOA is unknown. The antenna used in the experimental setup is a planar bow-tie antenna with a SiO2 substrate. The planar bow-tie antenna was chosen due to its slightly wider operating bandwidth as well as its higher input impedance. The use of misaligned planar bow-tie topology enables the construction of a more compact array with little changes to the radiating properties. The planar array resorted in the paper was a balanced line with 98.5Ω characteristic impedance with λ/4 number of transformers being deployed at each junction for matching reasons. Exploitation of a graphene ballistic diode was the main innovation of the research as the diode was used for THz rectification and worked up to 30 THz. Nonlinear simulation was then carried out by exploiting diode models and measured I-V characteristic of the graphene ballistic diode. Further extension of the cut-off frequency of the diode is needed, as well as improvements in the diode's rectification properties which would allow the diode to be directly compared with the MOM diode performance in solar energy harvesting, in order to further improve harvesting applications in the infrared frequency band of the graphene-based nano-rectenna.

The graphene-based antenna mathematical model for harvesting of energy in the ultraviolet (UV) spectrum utilizing Graphene based antenna was proposed (Vakil and Bajwa, 2014). The paper presented the graphene-based nanoscale antennas design and mathematical model for energy harvesting of the UV spectrum range frequencies. The quantum mechanical behavior of the graphene driven particle was taken into consideration in the calculation of current for the nanoscale antenna as the frequency range of the UV spectrum is much larger than that of the visible light. Another factor taken into consideration was the low irradiance of UV light. This was compensated by the power per photons of the UV spectrum due to the spectrum's extremely wide frequency. As per quantum mechanics, the quantum energy of electromagnetic radiation is proportional to that of its frequency. As such, the large frequency range of the UV spectrum not only excites electrons to move towards the valance shell, it also increases the conductivity of the nanoscale antenna while ensuring the electrons contain sufficient energy to increase the current produced by the antenna. The paper successfully proved analytically the possibility of graphene-based patch antenna being applied for UV spectrum energy harvesting. Figure 3 shows the graphene-based patch antenna's design which theoretically would exhibit excellent properties in the production of current.

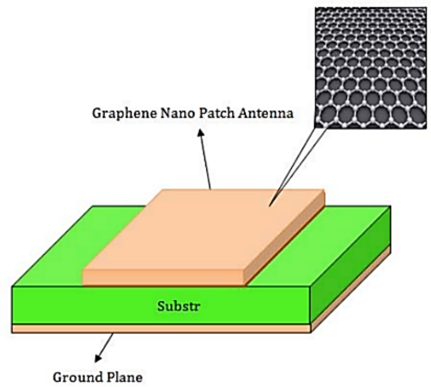

FIGURE 3. Graphene-based patch antenna design
Source: Vakil and Bajwa (2014)

Besides the screen-printing method to deposit graphene onto substrates, CVD is also one of the popular ways to deposit graphene onto substrate in the facilitation process of graphene antennas. The feasibility of ambient radio frequency energy harvesting using flexible, transparent graphene antennas for the field of self-sustainable machine-to-machine communication was investigated (Andersson et al. 2016). The energy harvested from the ambient radio frequency range aims to improve the sensor's battery life in IoT applications. Frequency bands between 900 MHz and 2.6 GHz were considered such as LTE, 3G, GSM and Wi-Fi due to the fact that these bands contain a large amount of ambient radio frequency energy. By the assumption of applications having transparency of above 80%, the limit of the graphene layers would be below 10 layers. CVD was used as the method would provide a better transparency compared to ink-jet printed graphene while the post-transfer surface treatment maximizes the concentration of the carrier while minimizing sheet resistance (Li et al. 2013). However, the method limits the CVD growth to a few layers hence requiring layer-by-layer transfer to ensure minimum sheet resistance. Based on the reported ambient radiofrequency intensity in both urban and rural environments, the range of harvested power in power budget examples were from 1 to 50 μW with the assumption of a diode-based rectifier due to graphene transistor rectifier efficiency being inferior. Results of the improve in battery lifetime shows significant improvement when the sensor reporting interval in the discontinuous reception (DRX) scheme in the order of a day. This time scale is relevant in future massive machine-to-machine communication systems for various envisioned sensors. However, the current graphene rectenna provides minimal usage in the conservative conditions and off-the-shelf transceivers. A key parameter in order to achieve a self-sustainable sensor in long reporting intervals is the transceiver base power consumption with the usage of the current best graphene dipole antenna. As transparent CVD graphene with a lower sheet resistance is currently unachievable, the prototype proposed in the paper was unable to compete with the current transparent metal grid antennas.

Zhang and Wang (2019) proposed a flexible wearable rectenna for wireless energy harvesting at 2.45 GHZ. The rectenna is designed as a simple circular polarized patch graphene film antenna (GFA). The substrate of the graphene antenna has a permittivity of 2.4 and a thickness of 0.9mm fed by a 50 Ω microstrip line. A class F rectifying circuit is simulated along with the antenna in order to increase conversion efficiency and simplify shunt rectifier circuit. The rectifier design is designed and optimized using ADS software. Simulated results show the proposed GFA rectenna exhibits a maximum conversion efficiency of 70% with 0 dBm input power and 900 mV output voltage in 0 dBm. The optimized GFA rectenna also exhibits low return loss and unidirectional radiation patterns.

A graphene-based bowtie circular array antenna was proposed for energy harvesting applications at infrared frequency 590 THz (Zakullah et al. 2019). The proposed array antenna consists of 8 radiating graphene unit cell configured in a circular array with a stacked substrate of silica on silicon material with thickness 70 and 50 nm respectively. The investigated antenna plasmon resonance at THz frequency and a peak gain of 4.9 dB. Simulation on the proposed antenna is done with the help of CST Microwave Studio software while the results are extracted using the frequency-dependent FDTD technique. Results shows best resonance at 590 THz where the proposed antenna has a return loss of -34 dB. Changes in the thickness of the graphene layer by parametric analysis effects the resonation frequency which having a lower return loss value. The increase in thickness of the graphene layer also changes surface plasmon resonance and the best absorbance of the proposed antenna can be observed from 500 THz onwards. The proposed antenna exhibits behavior of a directional antenna with a gain of 4.95 dB. The results of the simulation shows that the proposed antenna design could be utilized for the harvesting of infrared energy in the Terahertz frequency band.

(Citroni et al. 2022) proposed a rectenna design composed of a graphene arrow-bowtie nanoantenna with a metal-insulator-metal (MIM) diode integrated in order to harvest energy at the 28.3 THz frequency range. The graphene arrow-bowtie nanoantenna consists of two arrow shaped graphene sides facing each other divided by a small gap. In order to reduce nanoantenna impedance to obtain optimal matching of nanoantenna and rectifying diode, both arrowheads are cut longitudinally. The substrate of the nanoantenna is a stacked substrate consisting of silica and silicon dioxide materials. The nanoantenna is designed and simulated with the help of 3D CST 2021 software. The simulated results show a decrease in graphene sheets leads to a decrease in resonant frequency. The increase in electrochemical potential on the other hand leads to an increase in resonant frequency. As such, the tuning of the proposed device in order to achieve the targeted frequency could be obtained by adjusting the electrochemical potential and number of graphene sheets. Silicon oxide is used to fill the gap between arrowheads in order to simulate the device real behavior when MIM rectifier diode is present. The return loss of the device at 28.3 THz frequency is at 23.38 dB while the open circuit voltage indicates a value of 0.13 μV and short circuit current of 4.08 pA. By utilizing an NxM nano rectenna array, low pass filter and a DC-DC boost converter, the output voltage of the device achieved 3.3 V and an output current of 10 mA.

(Livreri et al. 2021) proposed a graphene nanoantenna design for infrared energy harvesting applications in the 28.3 THz frequency range. The proposed design consists of an arrow bowtie nanoantenna where opposite arrowheads facing each other are separated by a gap inserted with silicon oxide in order to simulate real conditions with the rectifying MIM diode. The substrate of the design is a three-layer substrate comprising of silicon oxide, high conductivity silicon and graphene material. The proposed nanoantenna is simulated using the CST Studio 2021 software. A sensitivity analysis was carried out in terms of geometric dimension, layer thickness and chemical potential. Simulation results indicates that the presence of the cut would influence the resonance frequency. The resonance frequency is also affected by the number of graphene sheets which exhibits a decreasing trend. Doping of the graphene material also affects the resonance frequency where the plot of resonant frequency against graphene electro-chemical potential shows a quasi-quadratic low plot. Simulation of a four-planar nanoarray design was also carried out where results show the area efficiency increases when the nano antennas are closer to each other.

TABLE 1. Comparison table of above research papers

Research Title	Year	Method	Frequency	Results	Result Type
Design and Testing of Graphene-Based Screen-Printed Antenna on Flexible Substrates for Wireless Energy Harvesting Applications	2021	Screen-Printed Antenna	2.45 GHz	150-270 mW, 50-100 mA, 2.4-5.2V, 23 dBm. Max efficiency: 43%	Both Simulation and Prototype
Graphene rectenna for efficient energy harvesting at terahertz frequencies	2016	Graphene transferred onto doped semiconductor	400-1100 GHz	Max efficiency: 58.43% at 897 GHz	Simulation Only
Multilayer screen-printed flexible graphene antenna for ISM band applications and energy harvesting	2020	Screen-Printed Antenna	2.45 GHz	50-100 mA, 2.4-5.2 V, 23 dBm	Both Simulation and Prototype
Graphene-based nano-rectenna in the far infrared frequency band	2014	Graphene ballistic diode	30 THz	46 pA.	Simulation Only
Energy harvesting using Graphene based antenna for UV spectrum	2014	Graphene-based patch antenna	UV spectrum	-	No simulations and prototypes
Feasibility of Ambient RF Energy Harvesting for Self-Sustainable M2M Communications Using Transparent and Flexible Graphene Antennas	2016	Chemical vapor deposition flexible antenna	900 MHz - 2.6 GHz	Dipole antenna ohmic efficiency: 5%	Simulation Only
A Flexible Wearable Rectenna for Wireless Energy Harvesting	2019	Graphene film	2.45 GHz	Max efficiency: 70% Output Voltage: 0.9V at 0 dBm	Simulation Only
Design and Analysis of Graphene Nano-Bowtie circular array Antenna for Energy Harvesting Applications	2019	-	590 THz	Reflection Coefficient: -34 dB Gain: 4.95 dB VSWR: 1.4	Simulation Only
A mid-IR Plasmonic Graphene Nano rectenna-based Energy Harvester to Power IoT Sensors	2022	-	28.3 THz	Output Voltage: 3.3V Output Current: 10 mA	Simulation Only
A 28.3 THz Plasmonic Graphene Arrow-bowtie Nanoantenna for Energy Harvesting	2021	-	28.3 THz	Tuning of antenna can be achieved by varying number of graphene sheets and electro-chemical potential.	Simulation on sensitivity analysis and planar array only

RESULTS AND DISCUSSION

Advancement and utilization of graphene-based material in the field of energy harvesting at microwave frequencies would greatly enhance the current sensor networks and systems powered by conventional battery sources. In order for graphene-based material to create an impact on the utilization in industry-standard systems, the synthesis of quality graphene in a large scale is of utmost importance. With sufficient supply of high-quality graphene, graphene-based materials used for energy harvesting could be further explored in order to further improve the parameters of the researched graphene-based antenna and systems to ensure that the graphene-based materials would have the ability to keep up with the demand of the market. Current researches made on graphene-based material for the harvesting of ambient energy are still in the simulations and small-scale prototypes stages. As most of the results obtained are theoretical or far from being optimal to suggest a change from the conventional methods being used, further improvements and research are still required on the optimization of the graphene material as well as antennas and energy harvesting system utilizing graphene.

Development and optimization of the graphene material in extending the life of graphene plasmons would further enhance the characteristics of the device operation. The merging of graphene antennas with metamaterials could also be explored in order to improve on the characteristics of the energy harvesting systems being proposed and researched on.

CONCLUSION

The paper reviewed on the evolution of graphene-based materials for the application of energy harvesting at microwave frequencies. The present state-of-the-art systems were discussed upon the designs, operations and prospects of these systems. While simulations and prototype of graphene-based material for radiofrequency energy harvesting have been demonstrated, practical realization of these energy harvesting systems into industry-standard systems still proved to be lacking. However, the recent progress on the fabrication of these systems showed promising futures and could be integrated into the industrial-standard systems if the lab-scaled prototypes could be move into fully functional, scalable demonstrators which are compatible with the current systems.

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DECLARATION OF COMPETING INTEREST

None

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