CASCATACHUVA
Humidity to Electricity

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Open Dialog in Applied Engineering 2025

Humidity-to-electricity conversion basics

1st – 8th of September 2025, Ölüdeniz, Türkiye

CASCATACHUVA Ltd
Prof. Andriy Lyubchyk

Universidade Lusófona · RMA Royal Military Academy · CascataChuva · Nanotechcenter · SYNYO · Anthesis Lavola

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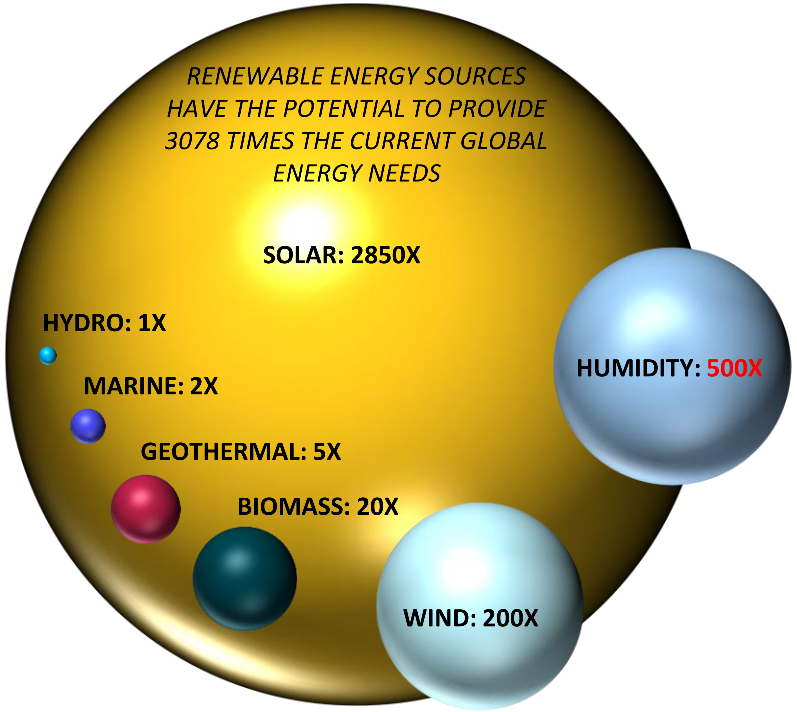
Energy Potential



- 1.3E+16 litters of water in atmosphere
- Adsorption energy of water 2240 kJ/kg (678 Wh)
- Overall source potential to provide 9600000 TWh of electricity

Atmospheric Humidity: Theoretical Energy Ceiling

Parameter	Value
Water mass in the atmosphere	**1.29×10^{16} kg**
Moles of H_2O	**7.17×10^{17} mol**
Global annual energy consumption	**170,000 TWh**
Latent adsorption energy (≈0.678 kWh/kg)	**8.75×10^{6} TWh** (~51×)
OH^- ions at 100% dissociation (1 per H_2O)	**4.32×10^{41} ions**
Electrochemical ceiling @ **0.5 V** (1 e^- per OH^-)	**9.60×10^{6} TWh** (~56×)

$$E=nFV$$

E — energy
n — number of moles of electrons (or moles of water at 1 e^- per OH^-)
F — Faraday constant
V — potential

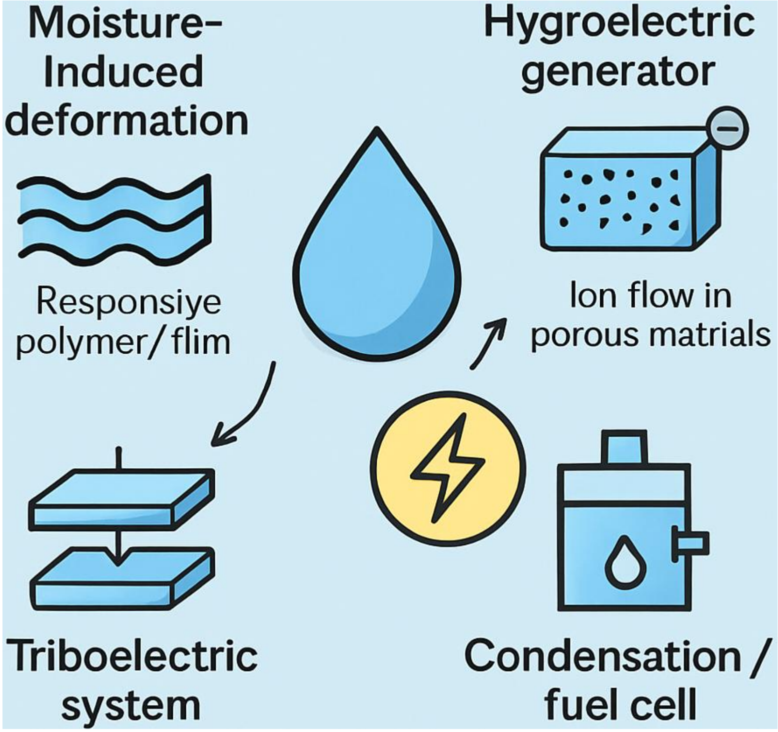
Energy Generation

Energy sources and its harvesting

Fossils:
Coal – 8000 W/kg
Oil – 12000 W/kg
Nuclear – 45000000 W/kg
Renewables:
Sun – 800-1300 W/m^2
Wind – 650 W/m^2 (10 m/s)
Atm Humidity – 678 W/kg

Wind	2.5 W/m^2
Plants	0.5 W/m^2
Solar PV panels	5–20 W/m^2
Tidal pools	3 W/m^2
Tidal stream	8 W/m^2
Rain-water (highlands)	0.24 W/m^2
Concentrating solar power (desert)	15–20 W/m^2

The harvesting system will be large, but the reservoir is huge, and generation is continuous



Humidity-to-Electricity Converter (HEC) – Existing Types

1.Moisture-induced deformation

Responsive polymers/films → very low, unstable output.

2.Hygroelectric generators (ion flow in porous materials)

Different sub-mechanisms, all pulsed/unstable:

- **Electrochemical contact** – water triggers redox at surfaces.
- **Pure ion transport – diffusion of $H_2O/H^+/OH^-$ through pores or gradients.**
- **Doped ion systems** – added ions (Na^+, K^+ etc.) carried by adsorbed water.

3.Triboelectric systems

Moisture-laden surfaces + external motion/vibration → need mechanical input.

4.Condensation / fuel-cell like setups

Liquid water, temperature gradients or chemical fuels required → not ambient-driven.

Summary and comparison of Humidity convertors

Active material	Electrode	Structure	RH level [%]	Output type	Electricity output	Refs.
CNPs	CNTs	Planar	–	Continuous	16.6 nW cm-2	1
g-GOF	Au	Sandwiched	30	Transient	0.42 mW cm-2	2
CNPs	Ag	Planar	100	Transient	50 mV, 0.6 nA cm-2	3
GO	Au, Ag	Sandwiched	80	Transient	30 mW cm-3	4
g-3D-GO	Al	Sandwiched	75	Transient	1 mW cm-2	5
TiO_2	FTO, Al	Sandwiched	85	Transient	4 mW cm-2	6
Gelatin	Au	Sandwiched	90	Transient	5.5 mW cm-2	7
CNPs	CNTs	Planar	–	Continuous	1.2 V, 20 nA cm-2	8
GO	rGO	Planar	60	Transient	70 mV, 12 mA cm-2	9
GO+QDs	Au	Planar	70	Transient	1.86 mW cm-2	10
PSSA	Carbon	Sandwiched	80	Transient	0.8 V, 0.1 mA cm-2	11
GOF	Au	Sandwiched	70	Transient	0.7 V, 25 mA cm-2	12
GO	Au	Sandwiched	70	Transient	0.72 V, 38 mA cm-2	12
Asymmetric GO	Au	Sandwiched	25	Continuous	0.45 V, 0.6 mA cm-2	13
GO+PAAS	Au, Ag	Sandwiched	80	Continuous	0.07 mW cm-2	14
Protein nanowire	Au	Sandwiched	50	Continuous	4 mW cm-3	15
Modified CNPs	CNTs	Planar	–	Continuous	5 V, 60 nA cm-2	16
CNPs	CNTs	Planar	–	Continuous	12.6 nW cm-2	17
Protein nanofiber	Pt	Sandwiched	55	Continuous	0.11 V, 22 nA cm-2	18
Na+ doped PPy	Au	Sandwiched	75	Transient	103 mW cm-2	19
CNTs	Ni, Cu	Planar	–	Continuous	2 mW cm-2	20
Cellulose paper	Stainless steel	Sandwiched	70	Transient	0.25 V, 10 nA cm-2	21
Wood	Carbon paste	Sandwiched	–	Continuous	18 nW cm-3	22
Si nanowire	Graphite, Ag	Sandwiched	–	Continuous	6 mW cm-2	23
GO fiber	Ag	Sandwiched	70	Transient	0.21 mW cm-2	24
GO	rGO	Planar	80	Transient	0.18 V, 9 mA cm-2	25
GO fiber	rGO	Planar	65	Transient	0.35 V, 1.06 mA cm-2	26
Graphite	Au	Planar	70	Transient	0.23 V, 0.4 mA cm-2	27
Al_2O_3	Carbon paste	Planar	–	Continuous	7.8 nW cm-2	28
Cotton+$CaCl_2$	–	Planar	37	Continuous	20 mWh cm-3	29
PDA	Ag	Sandwiched	90	Transient	0.52 V, 0.246 mA cm-2	30
Li+ doped PPy	Au	Sandwiched	85	Transient	690 nW cm-2	31
PSS–PVA	Ag nanowires	Sandwiched	85	Transient	7.9 mW cm-2	32
Al3+ doped PPy	Au	Sandwiched	75	Transient	40 mW cm-3	33
TiO_2+CNPs	Carbon ink	Planar	–	Continuous	1.6 V, 22 nA cm-2	34






Summary and comparison of Humidity convertors

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Streaming potential

$$U = \frac{8\varepsilon\varepsilon_0\zeta L}{\pi K R^4} Q$$

where,
R is the radius of the channel,
ζ is the zeta potential of the channel walls,
$\boldsymbol{\varepsilon\varepsilon_0}$ is the permittivity of the solution,
Q is the volumetric flow rate,
K is the conductivity of the solution,
L is the length of the channel.

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Gradient by adsorption properties – different adsorption properties of layers

Sun exposed device – sea water

Humidity gradient by deliquescent chemical

Summary and comparison of Humidity convertors

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ARTICLE

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https://doi.org/10.1038/s41467-022-30156-3 OPEN

Moisture adsorption-desorption full cycle power generation

Haiyan Wang[1], Tiancheng He[2], Xuanzhang Hao[2], Yaxin Huang[2], Houze Yao[2], Feng Liu[3✉], Huhu Cheng[1✉] & Liangti Qu[1,2✉]

Environment-adaptive power generation can play an important role in next-generation energy conversion. Herein, we propose a moisture adsorption-desorption power generator (MADG) based on porous ionizable assembly, which spontaneously adsorbs moisture at high RH and desorbs moisture at low RH, thus leading to cyclic electric output. A MADG unit can generate a high voltage of ~0.5 V and a current of 100 μA at 100% relative humidity (RH), delivers an electric output (~0.5 V and ~50 μA) at 15 ± 5% RH, and offers a maximum output power density approaching to 120 mW m^{-2}. Such MADG devices could conduct enough power to illuminate a road lamp in outdoor application and directly drive electrochemical process. This work affords a closed-loop pathway for versatile moisture-based energy conversion.

SiO_2 nanofiber, and rGO nanosheet

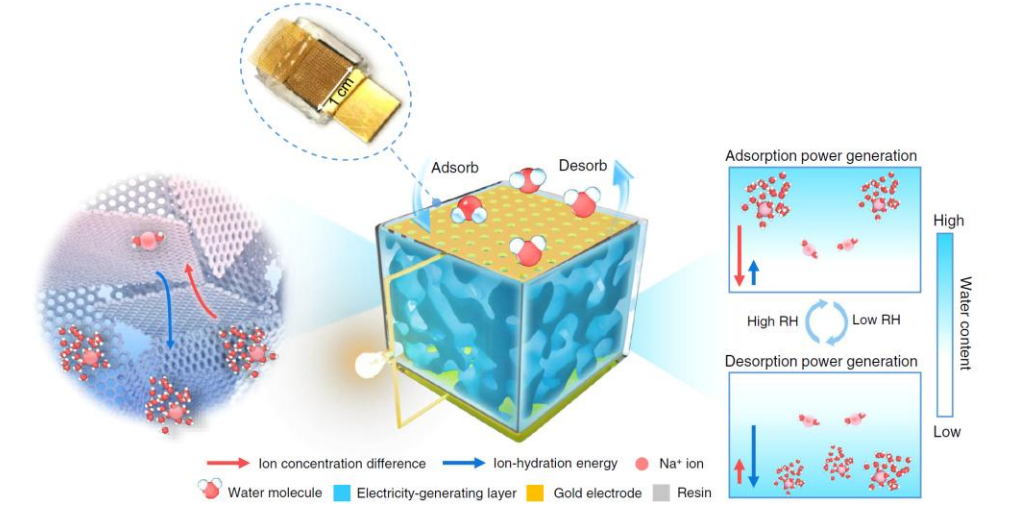
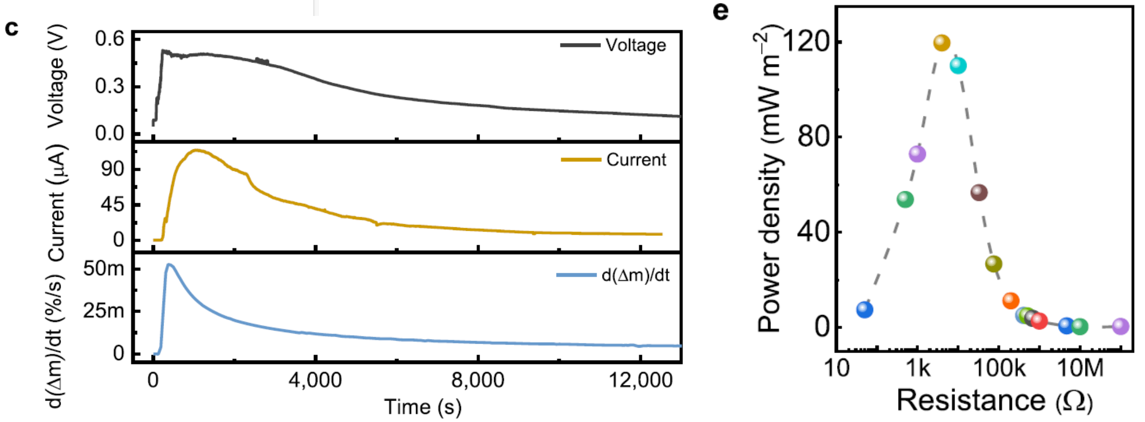


Fig. 1 Design of MADG. Scheme of the device structure, working principle, and photograph of device. The MADG is composed of gold electrodes, 3D ionizable porous assembly as electricity-generating material, and encapsulation layer, where the upper gold electrode has holes to allow entry/removal of moisture. Benefiting from well-designed structure, the MADG enables to deliver electric output under high and low RH condition through asymmetric moisture adsorption and desorption process, respectively. The electricity-generating principle is attributed to hydrated ions diffusion, driven by ion concentration difference during moisture adsorption power generation and dominated by ion-hydration energy during moisture desorption electricity generation, respectively.



Summary and comparison of Humidity convertors

nature nanotechnology

ARTICLES

https://doi.org/10.1038/s41565-021-00903-6

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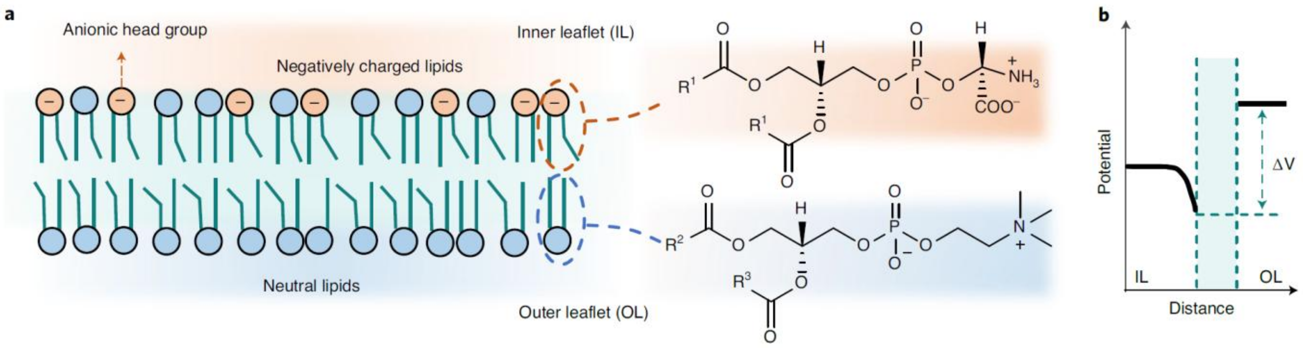
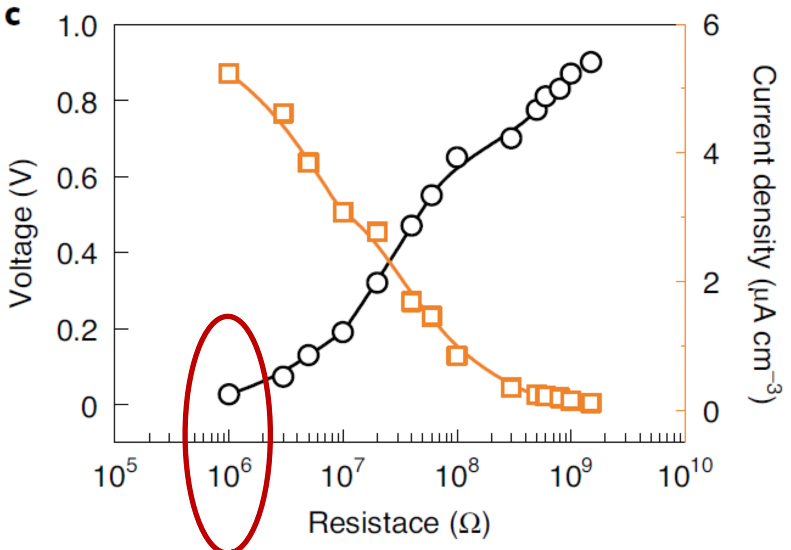
Bilayer of polyelectrolyte films for spontaneous power generation in air up to an integrated 1,000 V output

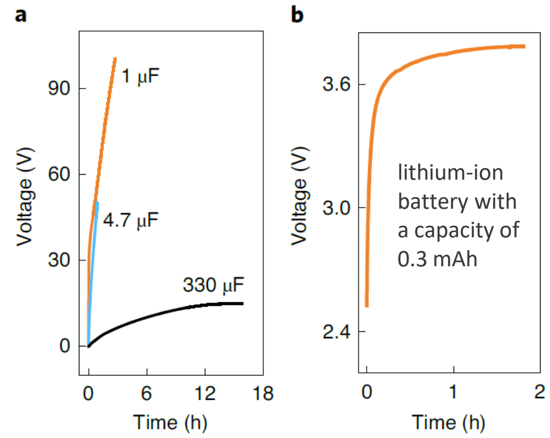
Haiyan Wang[1], Yilin Sun[2], Tiancheng He[1], Yaxin Huang[1], Huhu Cheng[1]✉, Chun Li[1], Dan Xie[2], Pengfei Yang[3], Yanfeng Zhang[3] and Liangti Qu[1]✉

Environmentally adaptive power generation is attractive for the development of next-generation energy sources. Here we develop a heterogeneous moisture-enabled electric generator (HMEG) based on a bilayer of polyelectrolyte films. Through the spontaneous adsorption of water molecules in air and induced diffusion of oppositely charged ions, one single HMEG unit can produce a high voltage of ~0.95 V at low (25%) relative humidity (RH), and even jump to 1.38 V at 85% RH. A sequentially aligned stacking strategy is created for large-scale integration of HMEG units, to offer a voltage of more than 1,000 V under ambient conditions (25% RH, 25 °C). Using origami assembly, a small section of folded HMEGs renders an output of up to 43 V cm⁻³. Such integration devices supply sufficient power to illuminate a lamp bulb of 10 W, to drive a dynamic electronic ink screen and to control the gate voltage for a self-powered field effect transistor.

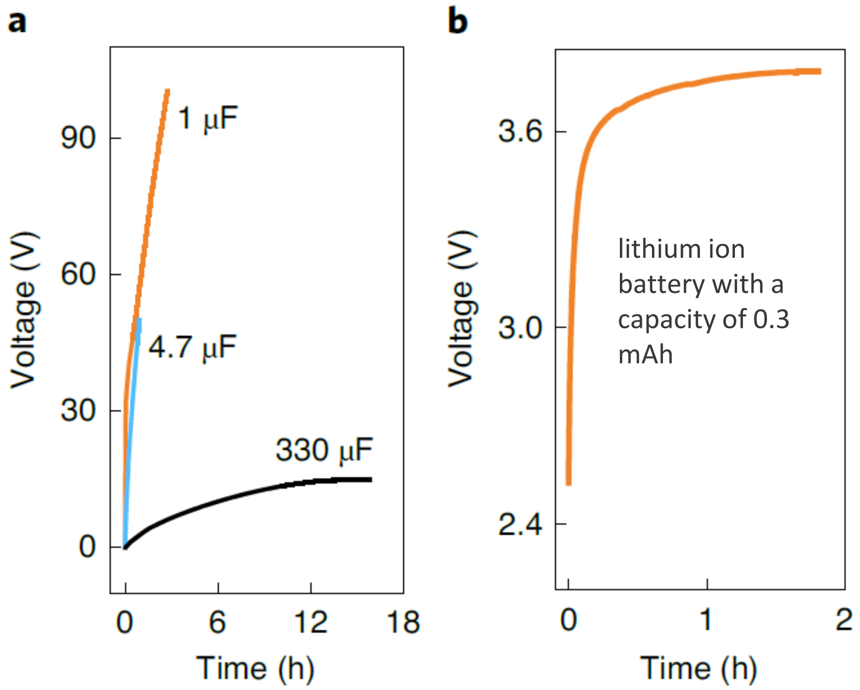




1 MOhm



Summary and comparison of Humidity convertors



Supplementary Note 5.

In our HMEG system, the electricity generation process of HMEG will stop when water adsorption tends to be saturated in HMEG (Supplementary Fig. 14). To achieve the electricity generation reversibility of HMEG, the absorbed water should be removed from HMEG to recover the water adsorption ability. Then, the HMEG could adsorb water from air again and re-generate electricity.

As demonstrated in Supplementary Fig. 15a, after the completion of first water absorption and electricity generation process, HMEG is then dried at 45°C (~12 h) for water dehydration. The dehydrated HMEG can generate similar current when exposed to air (20% ~ 30% RH) once again, which confirms that the reversible electricity generation of HMEG can be achieved

Summary and comparison of Humidity convertors

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Article

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Green moisture-electric generator based on supramolecular hydrogel with tens of milliamp electricity toward practical applications

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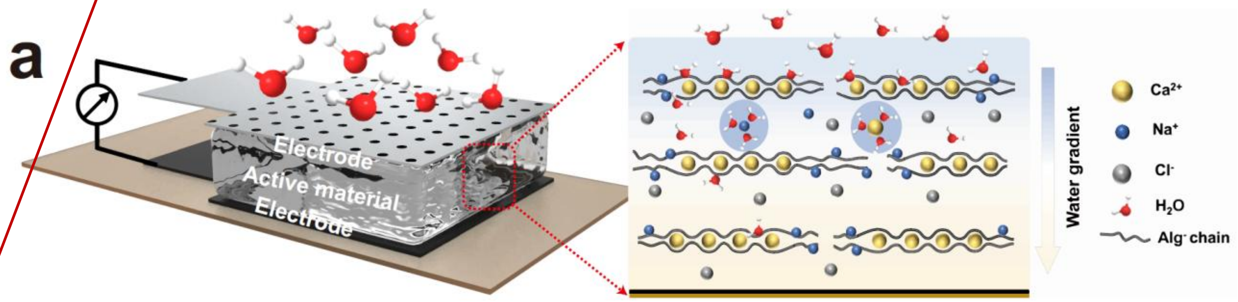
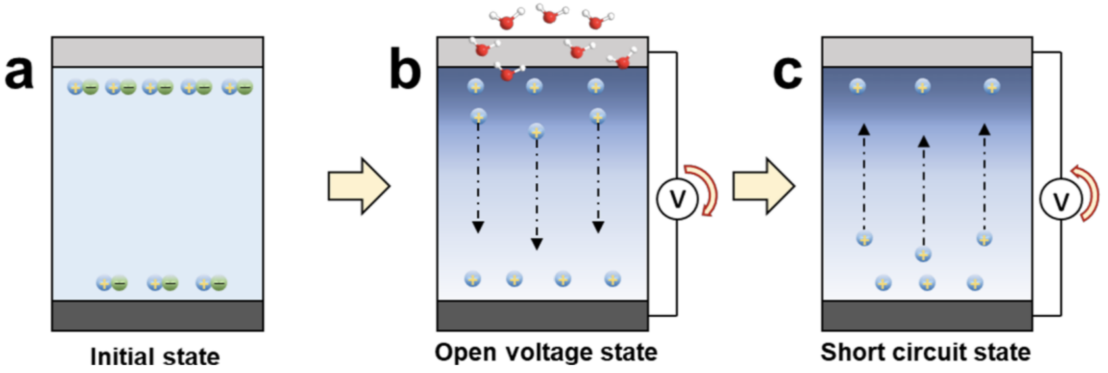
Check for updates

Su Yang [1,2], Lei Zhang[3], Jianfeng Mao[4], Jianmiao Guo [4], Yang Chai [4], Jianhua Hao [4], Wei Chen [5] & Xiaoming Tao [1,2]

Moisture-electric generators (MEGs) has emerged as promising green technology to achieve carbon neutrality in next-generation energy suppliers, especially combined with ecofriendly materials. Hitherto, challenges remain for MEGs as direct power source in practical applications due to low and intermittent electric output. Here we design a green MEG with high direct-current electricity by introducing polyvinyl alcohol-sodium alginate-based supramolecular hydrogel as active material. A single unit can generate an improved power density of ca. 0.11 mW cm^{-2}, a milliamp-scale short-circuit current density of ca. 1.31 mA cm^{-2} and an open-circuit voltage of ca. 1.30 V. Such excellent electricity is mainly attributed to enhanced moisture absorption and remained water gradient to initiate ample ions transport within hydrogel by theoretical calculation and experiments. Notably, an enlarged current of ca. 65 mA is achieved by a parallel-integrated MEG bank. The scalable MEGs can directly power many commercial electronics in real-life scenarios, such as charging smart watch, illuminating a household bulb, driving a digital clock for one month. This work provides new insight into constructing green, high-performance and scalable energy source for Internet-of-Things and wearable applications.

Voc-1.3V	Ads – 60%wt
Jsc-1.31 mA/cm2	$CaCl_2$
P - 0.11mW/cm2	RH - 80%





Long term gradient – 30 days

Fast adsorption – 240 mins

Scope and overview of project

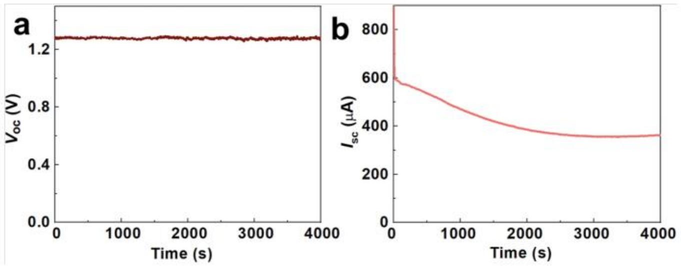
Summary and comparison of Humidity convertors

catcher

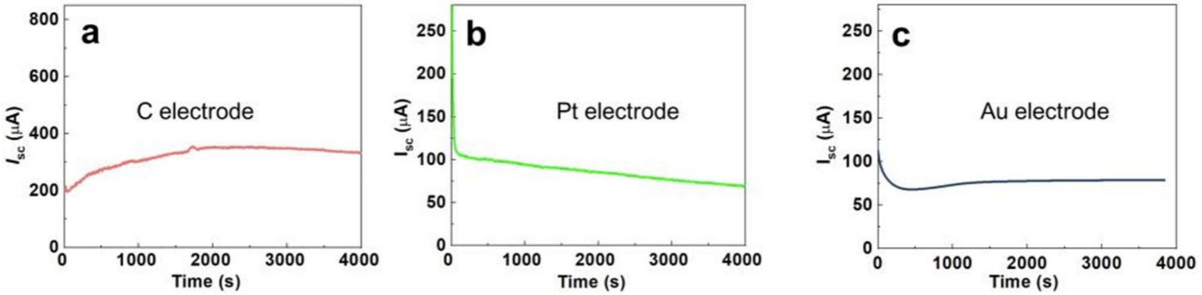
Results

Structure and electric output of one MEG device

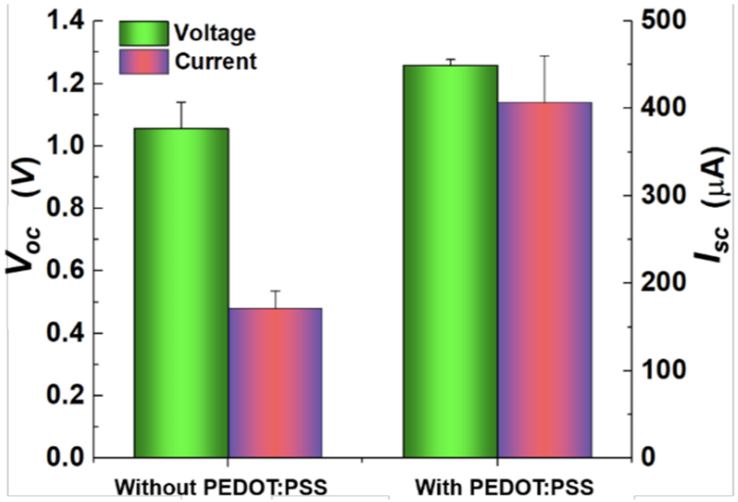
As shown in Fig. 1a, one single MEG device consists of a green electricity-generating layer and a pair of asymmetric electrodes. The electricity-generating layer is well-designed by molecular engineering AlgNa into PVA hydrogel. Non-ionic polyhydroxy PVA is easy to construct a physical cross-linked network with hydrophilic property. As a natural polysaccharide, the polyanionic AlgNa features with numerous hydroxyl groups (Supplementary Fig. 1), thus presenting prominent water-affinity feature, which is expected to enhance the water absorption of MEG. Moreover, by adding crosslinker of $CaCl_2$, an obvious blue shift of −COO− stretching band is observed in Fourier Transform Infrared Spectroscopy (FTIR) spectrum, suggesting the crosslinking Ca^{2+} with −COO− of AlgNa[25]. That means supramolecular AlgCa/Na ionically cross-linked network is formed with abundant carboxyl functional groups (e.g., -COONa and -COOCa) as depicted in Fig. 1a[26], which plays a key role as dissociable ions when interacting with water molecules. Besides, a pair of asymmetric electrodes were established by directly laser-induced graphene as bottom electrode on polyimide (PI) substrate and aluminum (Al) film with holes as top electrode, which are conducive to large-scale integration efficiently and improve output performance of MEG device[10,17]. Additionally, Al film is highly flexible, lightweight, easily accessible and fairly cheap, which is desirable for scalable and low-cost MEGs towards wide applications[27,28]. Poly(3,4-ethylenedioxythiophene): poly(styrene sul-



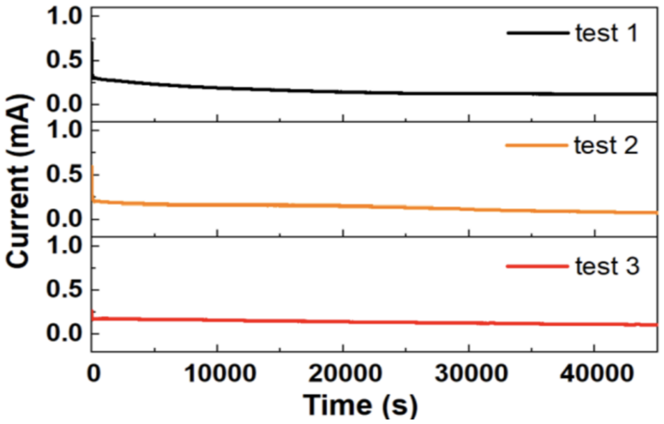
Supplementary Figure 8. The V_{oc} (a) and I_{sc} (b) output of MEG tested at 80 % RH in a N_2 environment.



Current output decrease on Pt, Au contacts. Used electrodes Al-C



PEDOT Oxydation?



1. Need for dehydration
2. Decrease of performance for following cycles

1. Most of the porous materials of appropriate design/properties allow HEC
2. Continuity of the HEC process is still not resolved
3. Ions movement is the main driver for HEC
4. Amount of adsorbed water is crucial for HEC performance

Conversion Mechanism

Mechanism of Humidity-to-Electricity Conversion

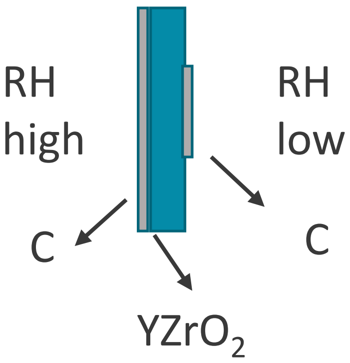
1. **Adsorption of water vapor** on porous/ionic material surface.
2. **Dissociation of H_2O molecules** into mobile charge carriers (H^+, OH^-).
3. **Selective ion transport** inside nanochannels: surface charges guide one type of ion, blocking the other.
4. **Charge separation** creates an internal electric field across the device.
5. **Conversion to electronic current**: ions drive electron flow through the external circuit → continuous DC output.

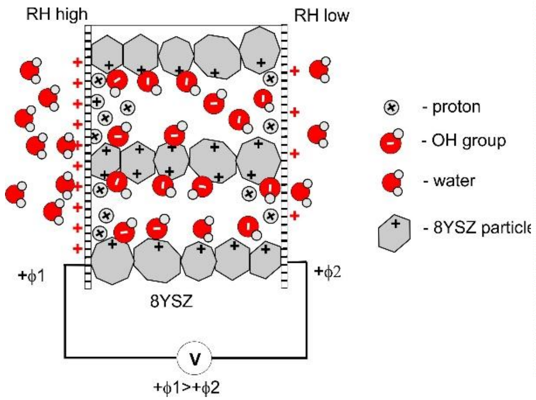
Electrode Reactions:

Anode (OH^- side): $4OH^- \rightarrow 2H_2O + O_2 + 4e^-$

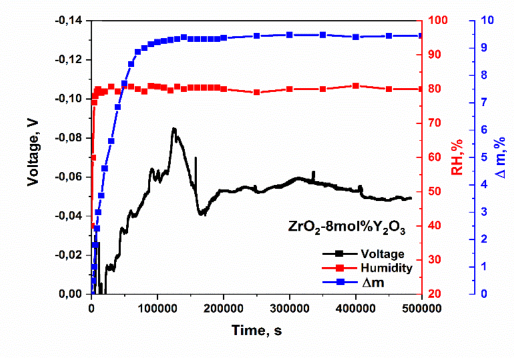
Cathode (H^+ side): $4H^+ + 4e^- \rightarrow 2H_2$

I generation





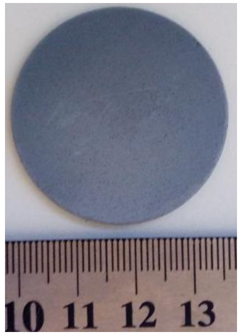
pH = 3.5 ~ $10^{-10.5}$ OH^-



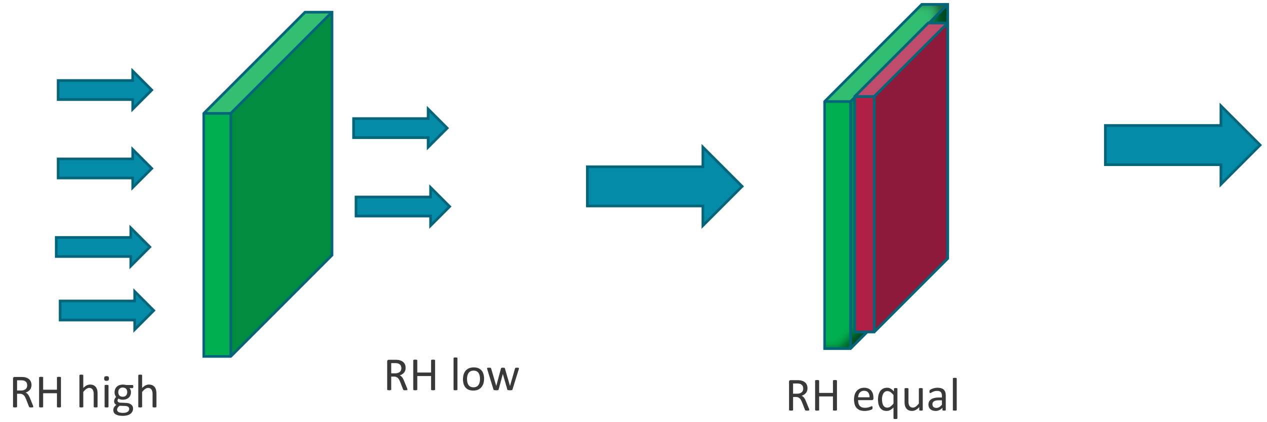
$$U = \frac{8\varepsilon\varepsilon_0\zeta L}{\pi K R^4} Q$$

V_{oc} ~100 mV

I_{50k} ~ 40 nA



CATCHER achievements – gradient problem



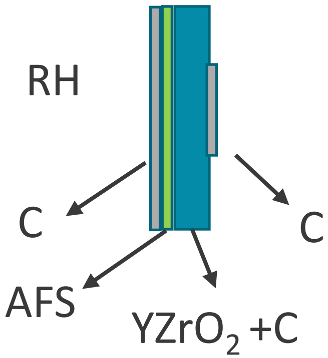
$[Al(H_2PO_4)_3]n$

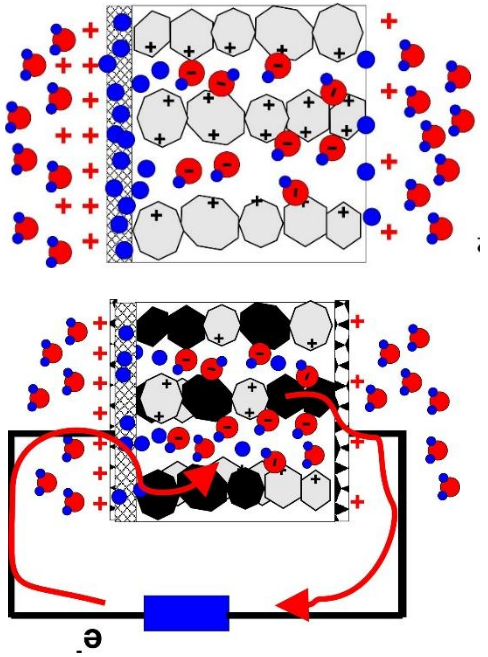
$H_2PO_4^- + H_2O \leftrightarrow HPO_4^{2-} + H_3O^+$. Kd=7.2

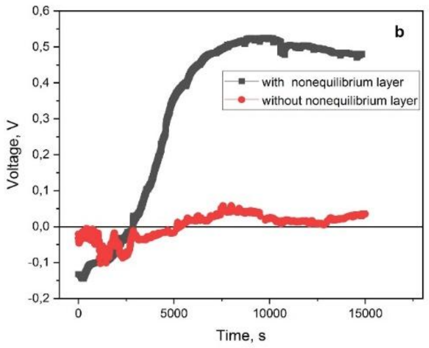
$HPO_4^{2-} + H_2O \leftrightarrow H_2PO_4^- + OH^-$ Kh = 6.8

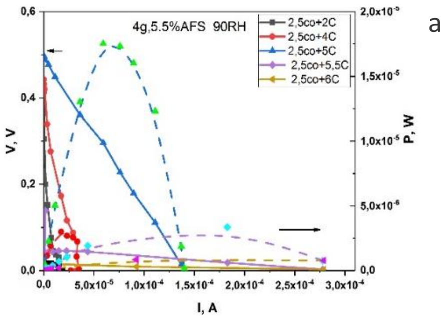
$\frac{dRH}{dx} \rightarrow \frac{dC}{dx}$ H^+, OH^- continuous

I generation









$$j_i = -D_i\left(\nabla c_i + \frac{z_i F c_i}{RT}\nabla\varphi\right)$$

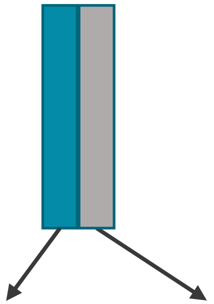
10 nW electric power in the load 280 kOhm.

$$\nabla \cdot j_i = \frac{\partial c}{\partial t}$$

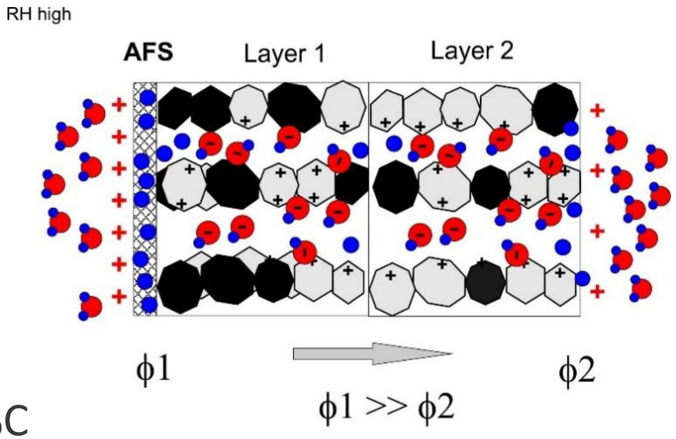
Electric power 18 μW
Graphite concentration - 5 wt%, AC - 2.5wt%
The internal resistance decreased in 500 times to 3 kOhm

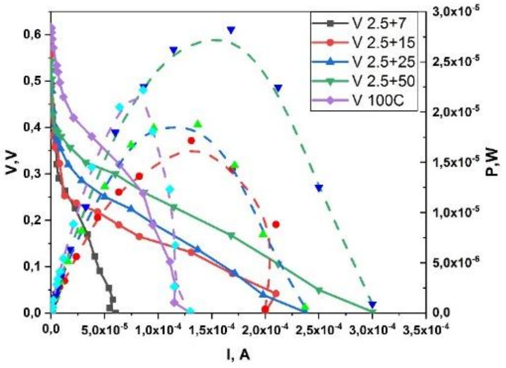
CATCHER achievements

II generation



$YZrO_2$+50%C $YZrO_2$+7,5%C



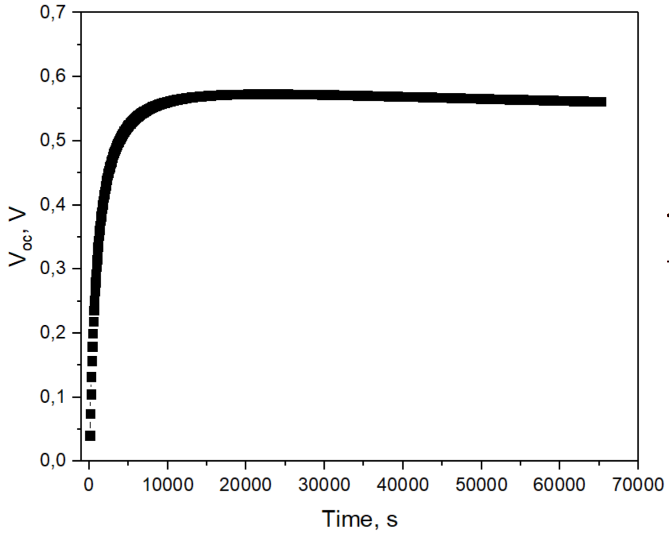


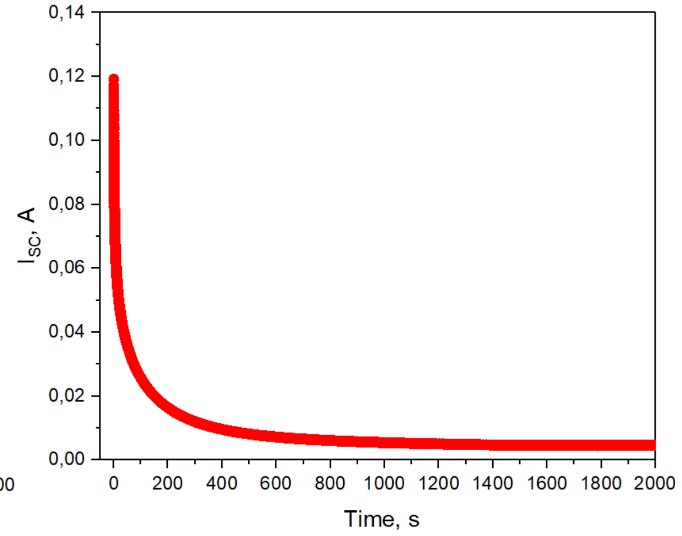
Increasing of graphite concentration in the second layer led to increase of the electric power from 5.7 μW to 28 μW, wherein the internal resistance decreased from 5 to 1 kOhm

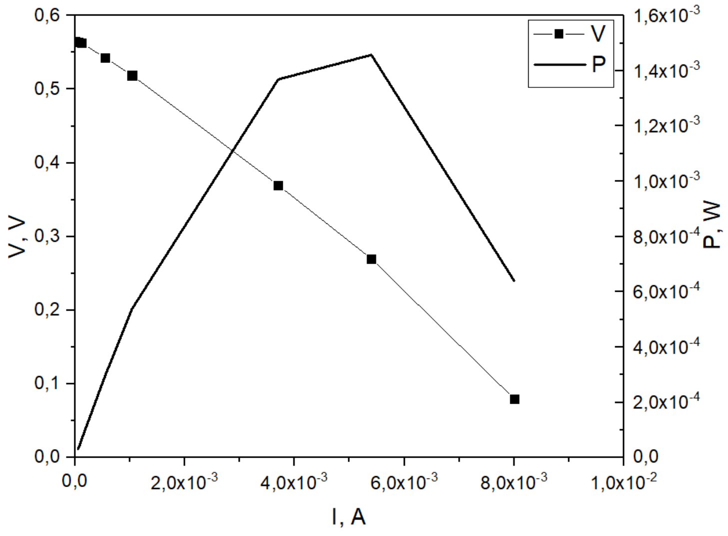
III generation +

$$E = \frac{RT}{zF} ln \frac{K_e}{K_i} = 0.059 \lg \frac{K_e}{K_i}$$

E_{max}=0.826 V





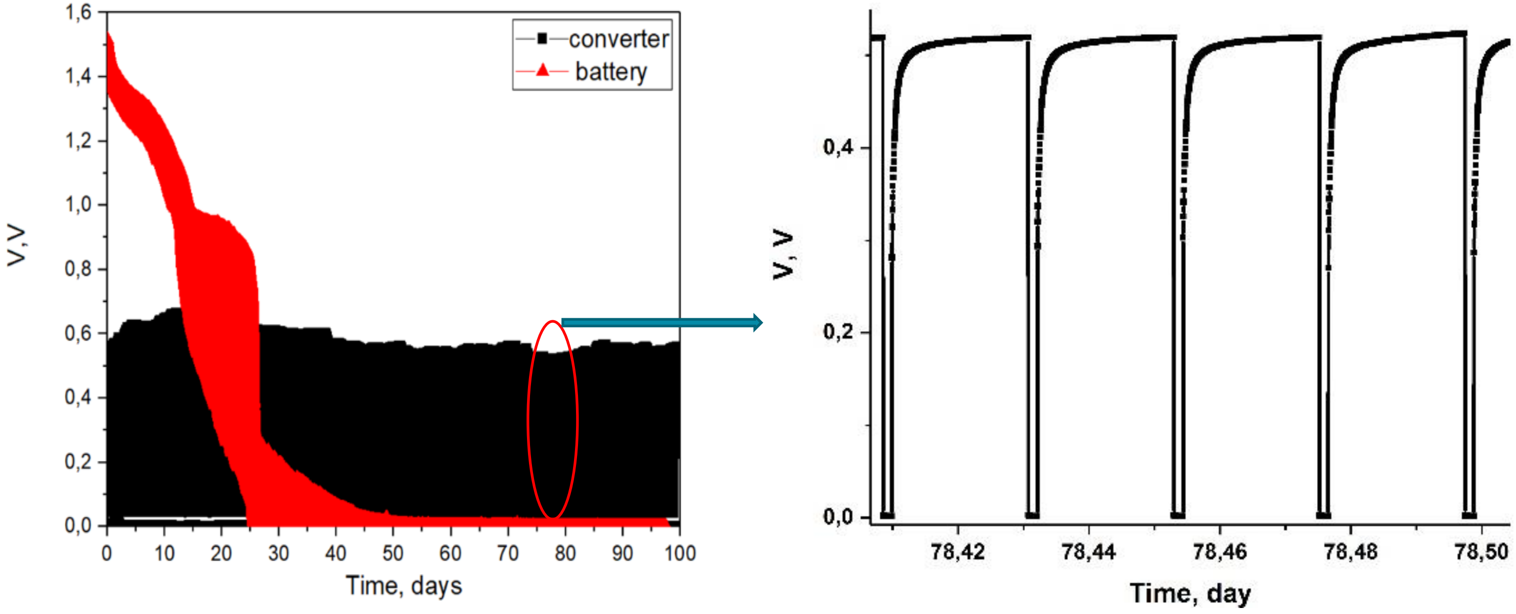


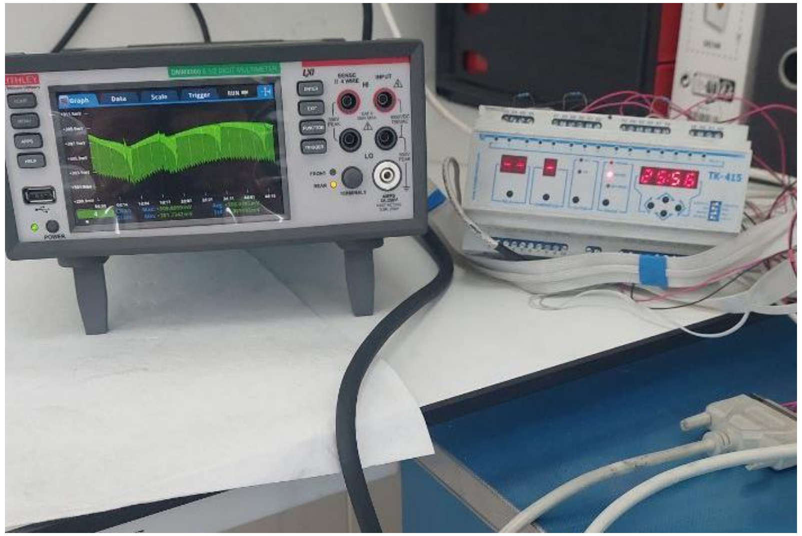
HEC converters generates:
V_{oc} – 500-550 mV
$I_{\_imp}$ – 120 mA
R_{opt} –100 Ohm
I_{opt} – 6 mA
P_{opt} – 1.5 mW

Conversion Stability

Comparison of working cycles of converter and 1.5V AA battery

Cycle: 1mins - 10 Ohm, 30mins – recovery, RH 80%





AA battery complete depletion 30 days

Conclusions

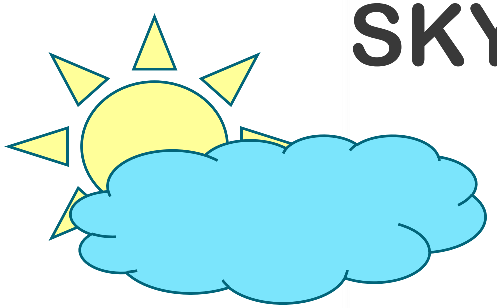
(i) Development the structure with anisotropy with respect to surface properties of materials with the aim to increase the amount of charge carriers in the reaction zone.
(ii) Increasing of the number of the reaction zones (3D net electrodes) for the increasing the number of electrons generated/donates in the converter;
(iii) Obtaining multilayer architectures with a gradient of acidic/basic properties to increasing the number of charges generated on both sides of the converter, capable of providing the maximum possible flow of electrons in the external circuit.

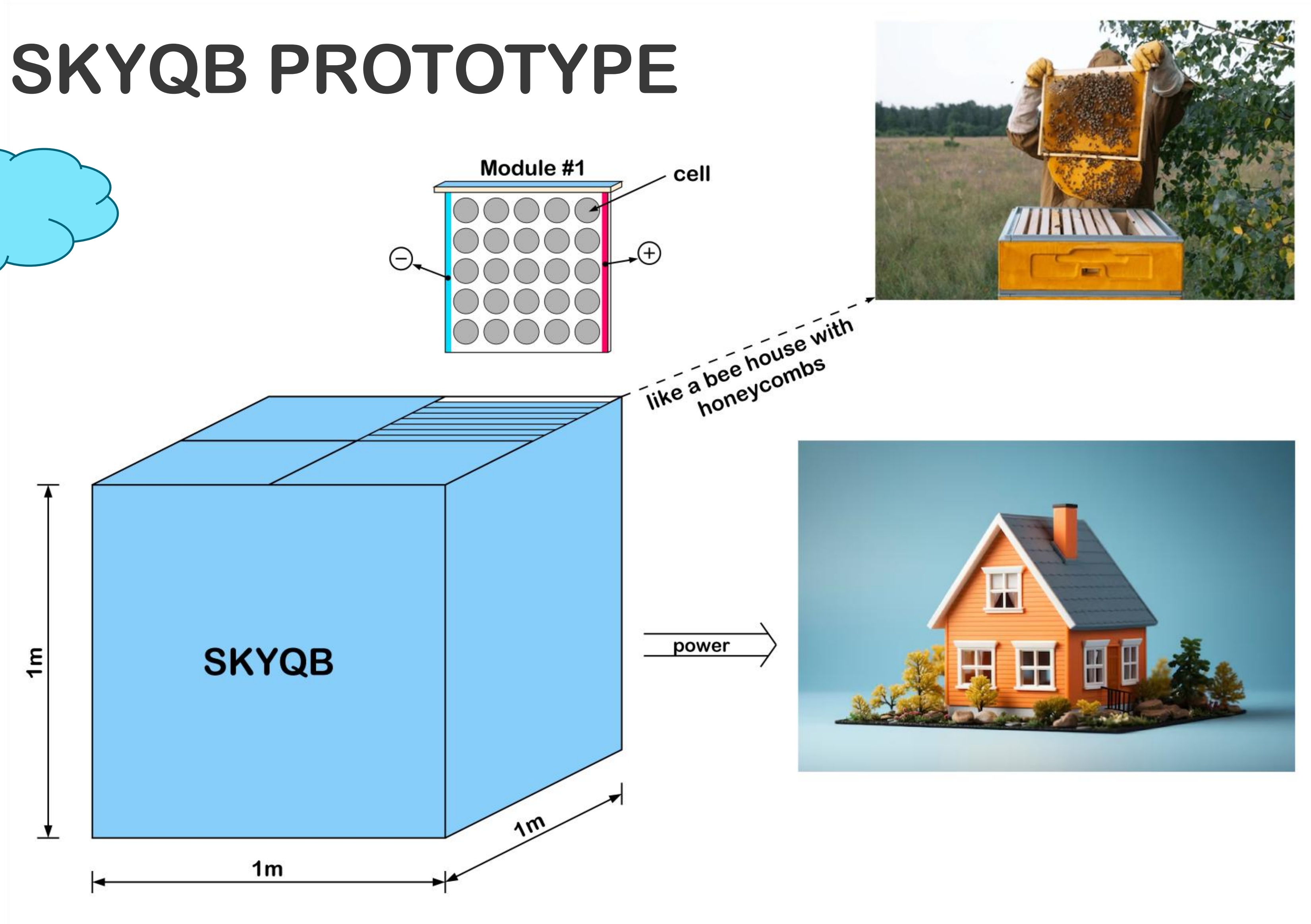
#	P, W	R_{in}, Ohm
One layer 8YSZ	$5.8*10^{-9}$	500000
One layer 8YSZ+AFS	$10.5*10^{-9}$	280000
Gen I⁺	$18*10^{-6}$	3000
Gen II	$35*10^{-5}$	1000
Optimized Gen III⁺	$1.5*10^{-3}$	50-100

Output Power increased in ~260 000 times

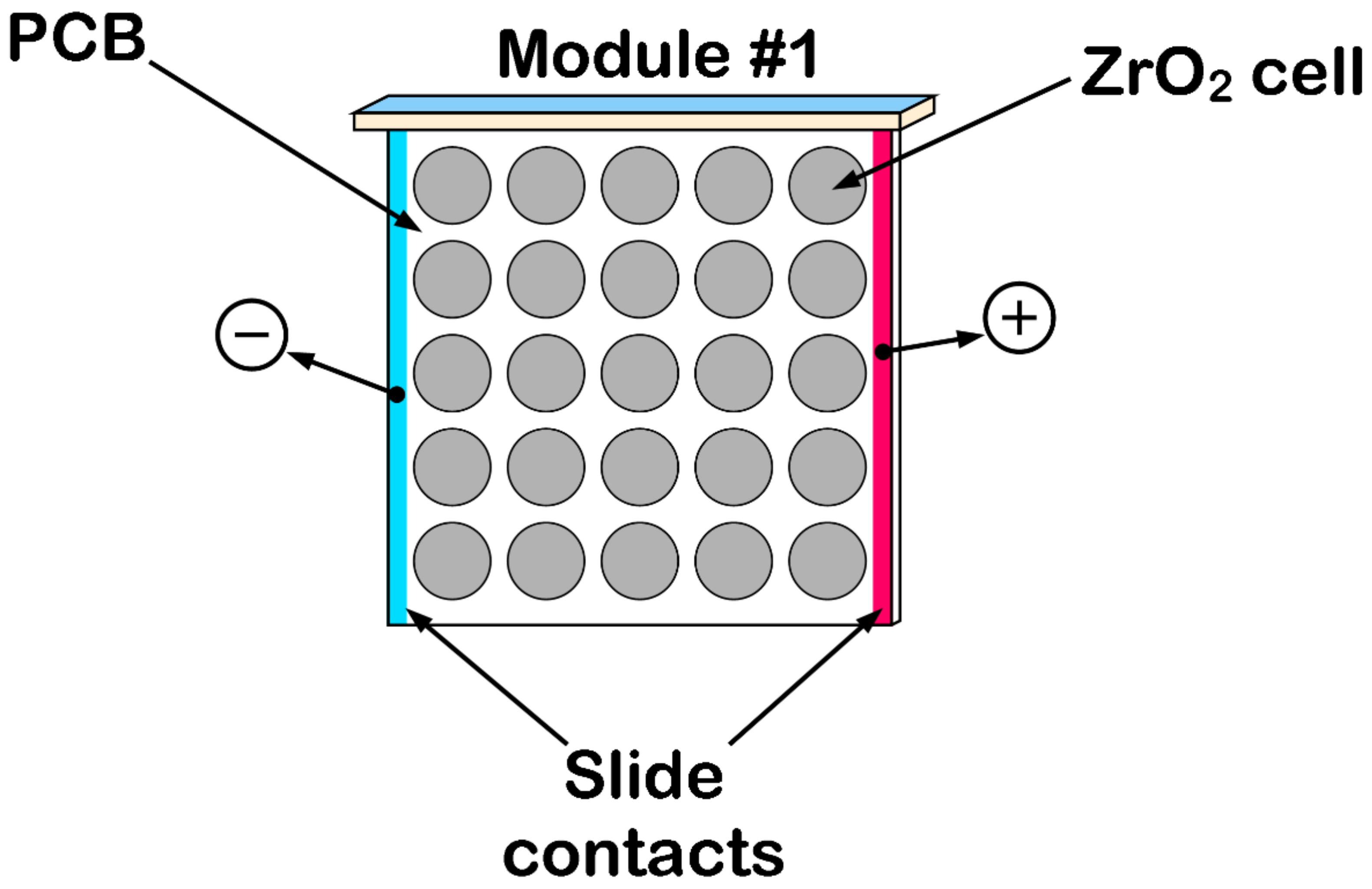
SkyQB design

catcher

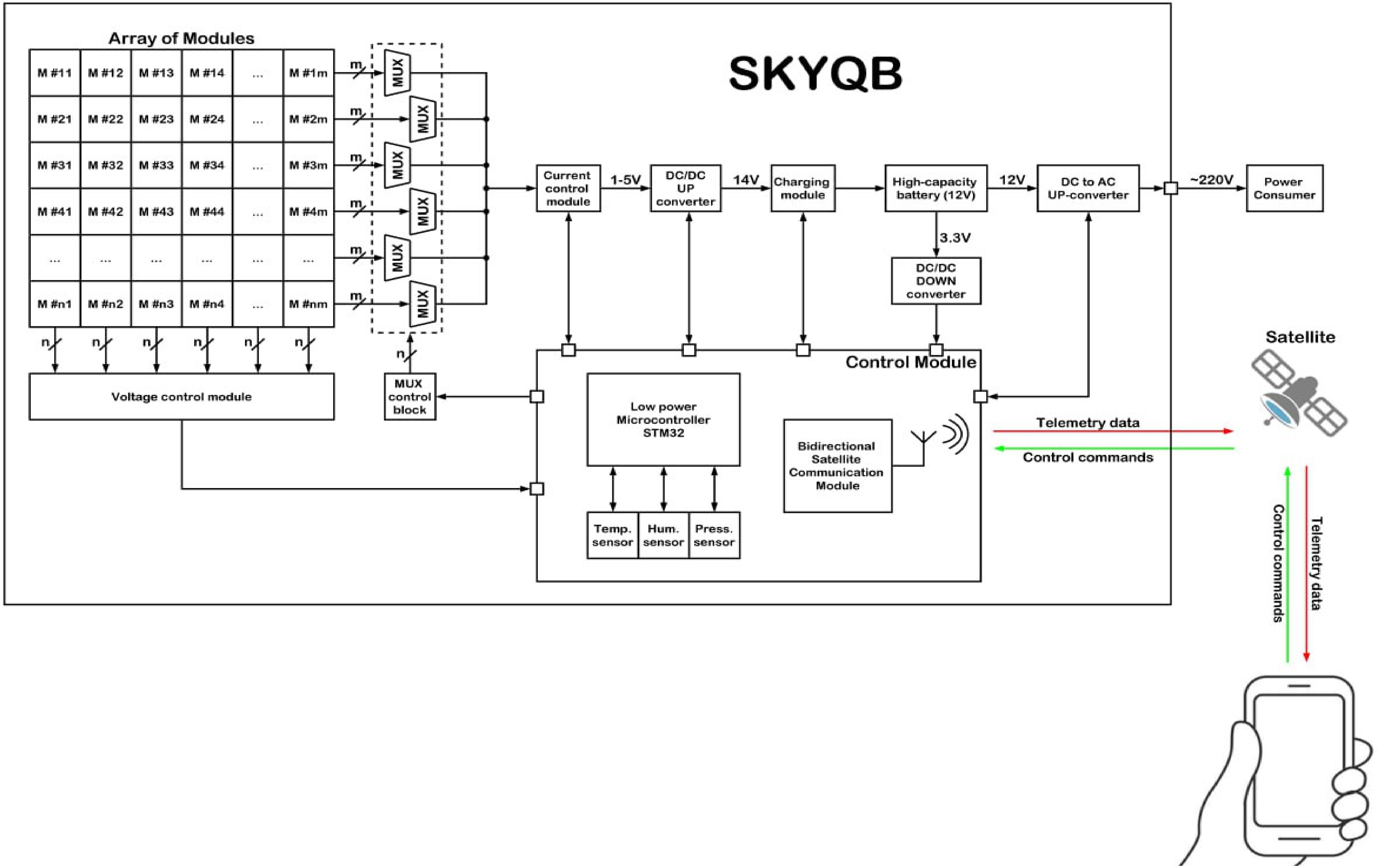




SkyQB design



SkyQB design



Acknowledgements

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