Printed (Electronic) Devices of Things (**PDoT**)

Enabling Nanotechnology and Printed Electronics for the IoT sector

https://pdot.tech

From Nanomaterials and Nanoinks to Printed Electronic Thermoelectric Devices for thermal energy harvesting

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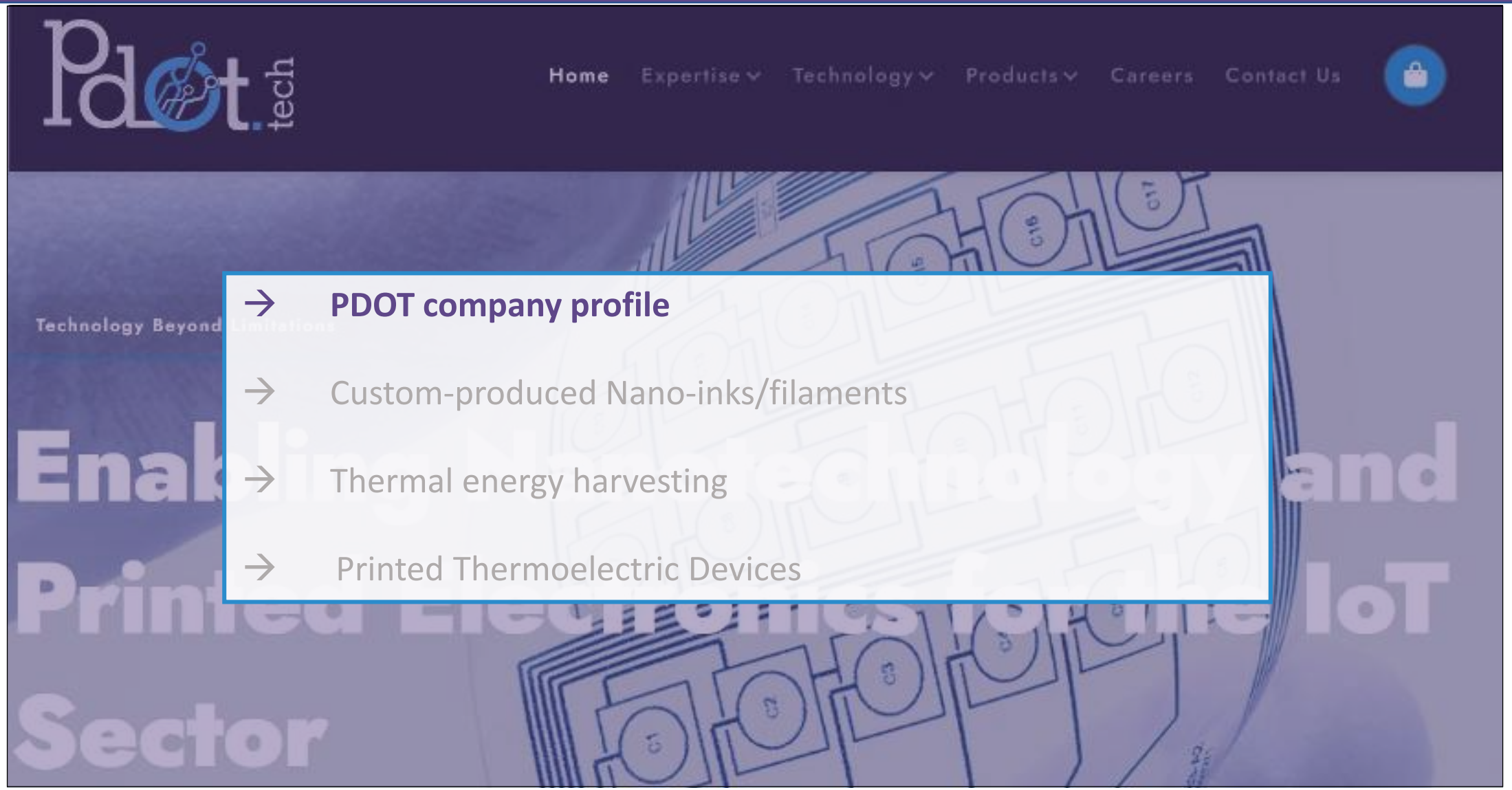
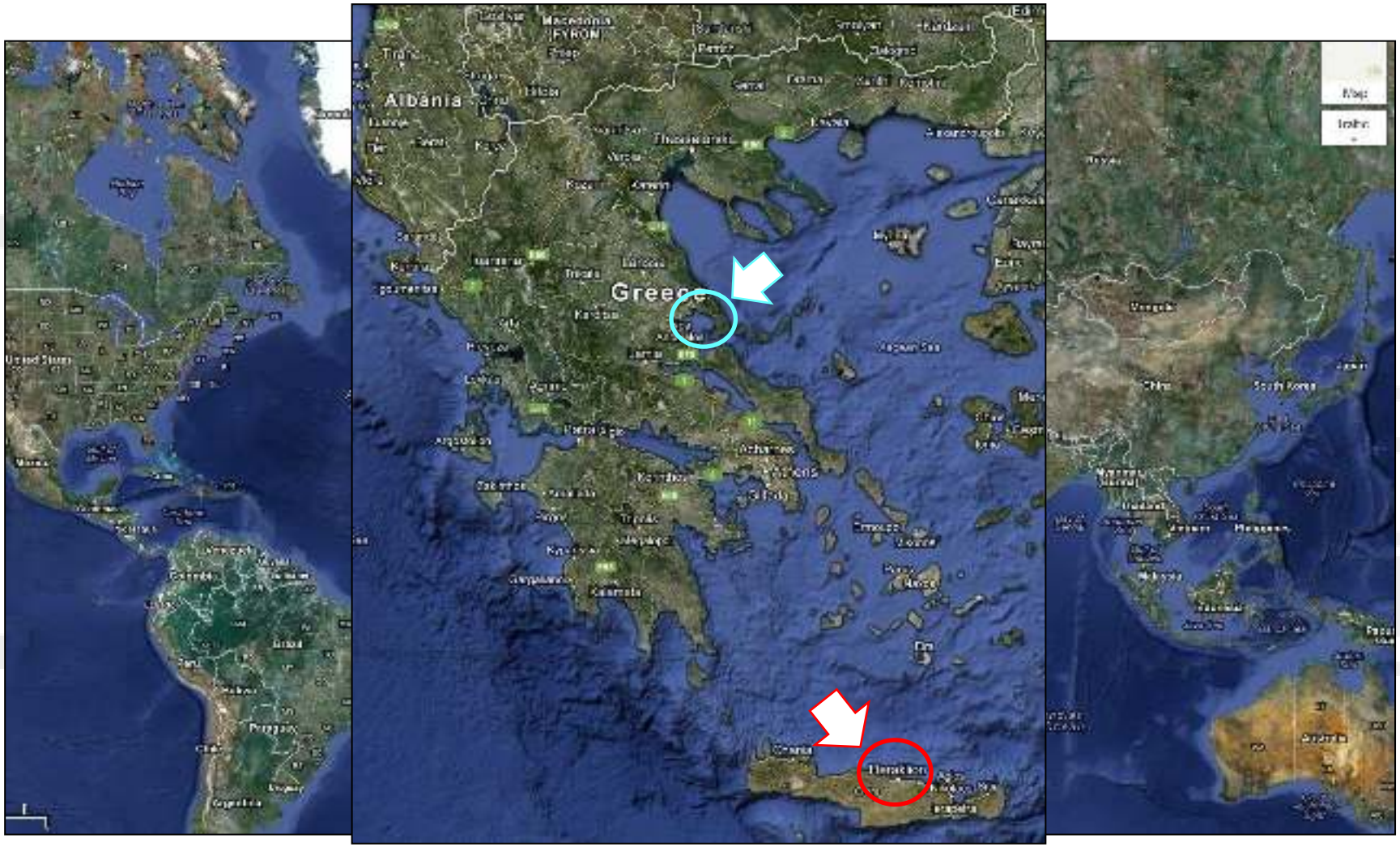
Outline



- → **PDOT company profile**
- → Custom-produced Nano-inks/filaments
- → Thermal energy harvesting
- → Printed Thermoelectric Devices

@ a glance.. locations in Greece: Volos – Heraklion founded in 2019..



PDOT tech team

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Infrastructure – Facilities (01): Synthesis-Processing & 2D wet-chemical deposition techniques





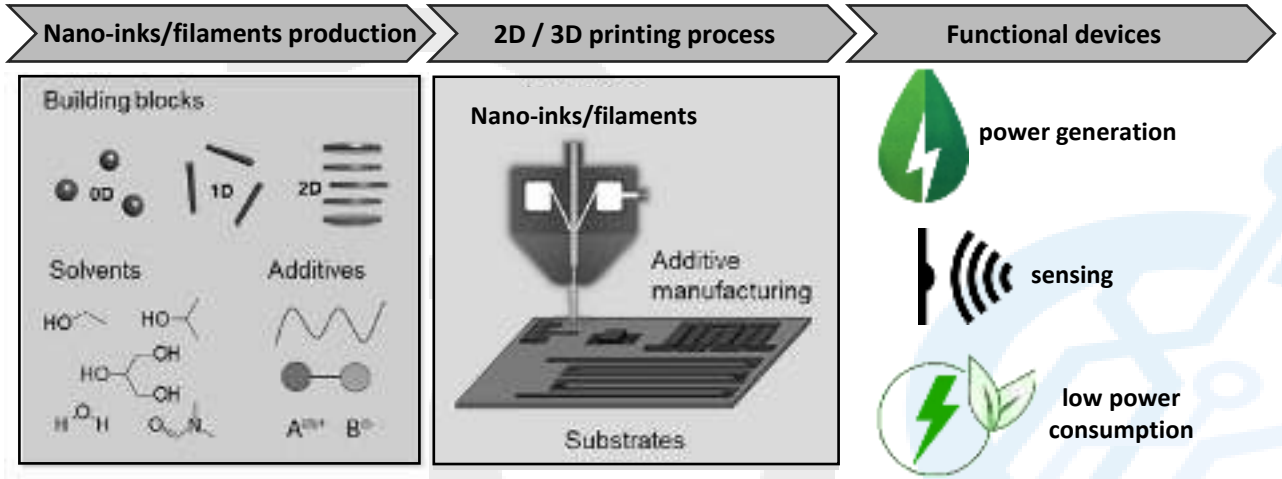


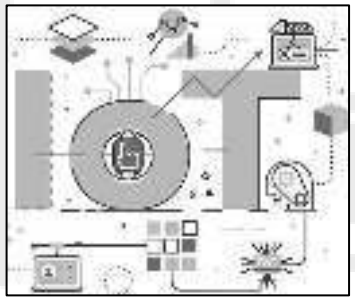

Infrastructure – Facilities (02): Filament extruders & 3D printers

Infrastructure – Facilities (03): Characterization tools

PDOT.tech vision

*"Enabling **Nanotechnology** advancements towards sustainable & low-cost **printed electronics** for IoT"*





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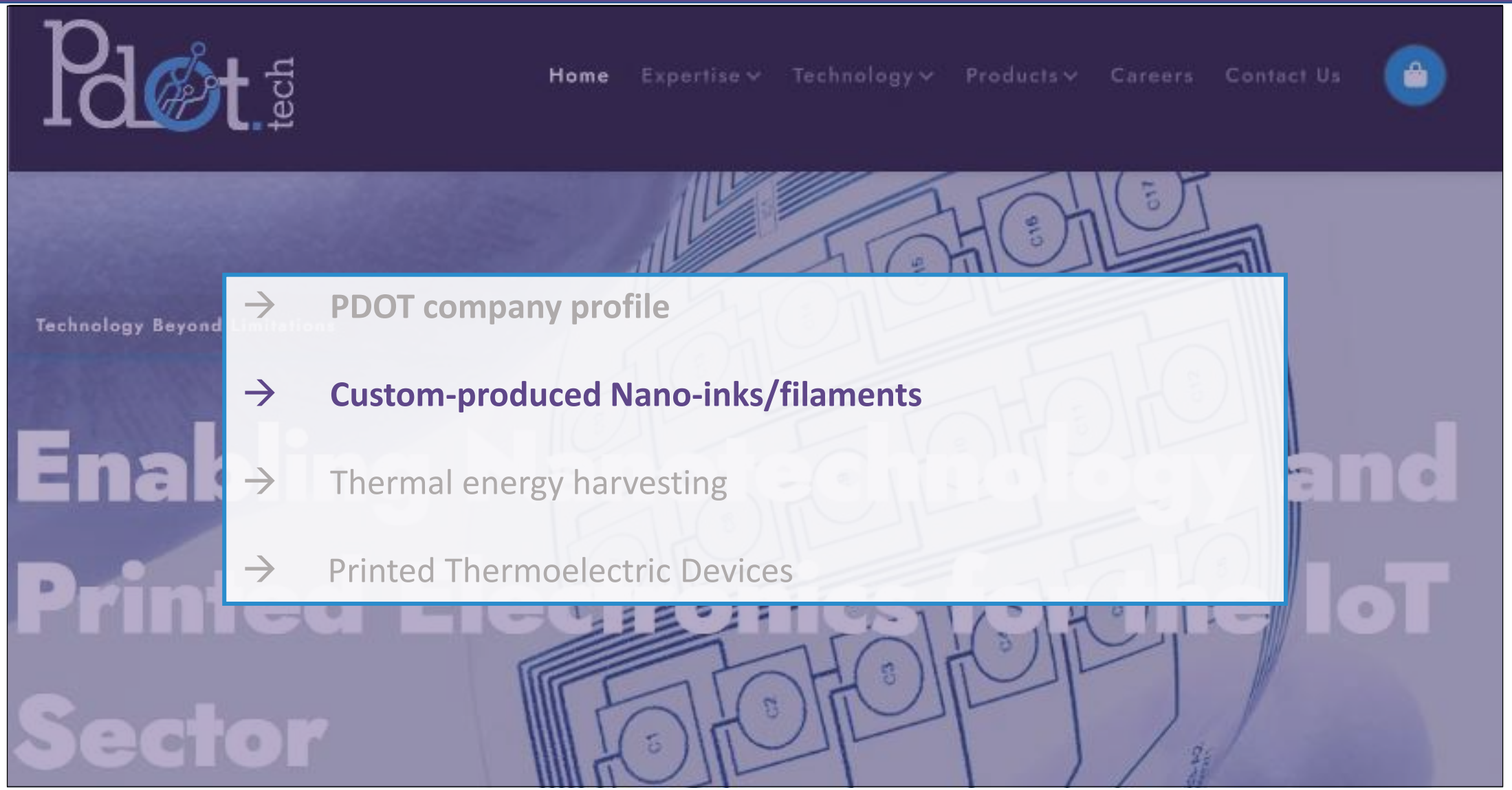

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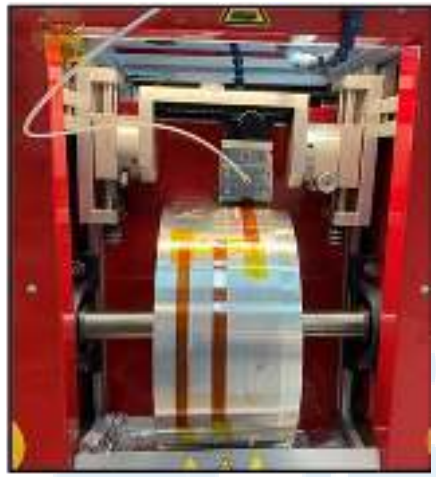
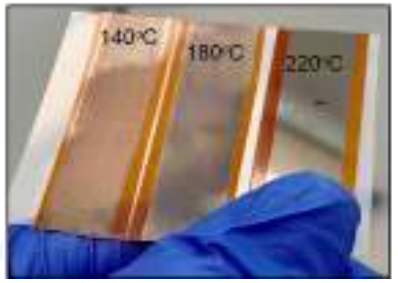
printed conductive Ag-NPs based trucks-circuits

Ethanol solvent





Key features of Printed Circuits include:

- ✓ low-cost
- ✓ thin-flexible
- ✓ lightweight
- ✓ highly conductive (10^5-10^6 S/m)
- ✓ low-temperature annealing (140-220°C)

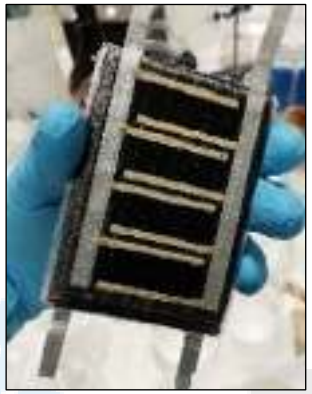
printed conductive C-NPs based trucks-circuits

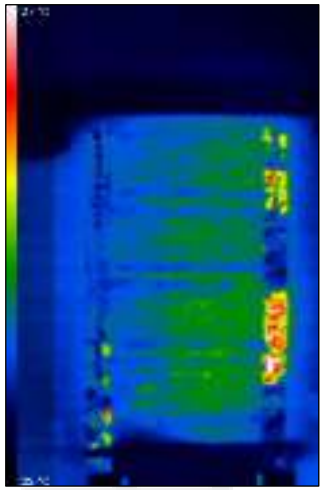
Aqueous or IPA solvent

Key features of Printed Circuits include:

- ✓ low-cost
- ✓ thickness controlled
- ✓ lightweight-flexible
- ✓ various conductive grades (10^3-10^5 S/m)
- ✓ low-temperature drying (55-95°C)

printed C-NPs based electrothermal heaters





Key features of Printed Film Heaters include:

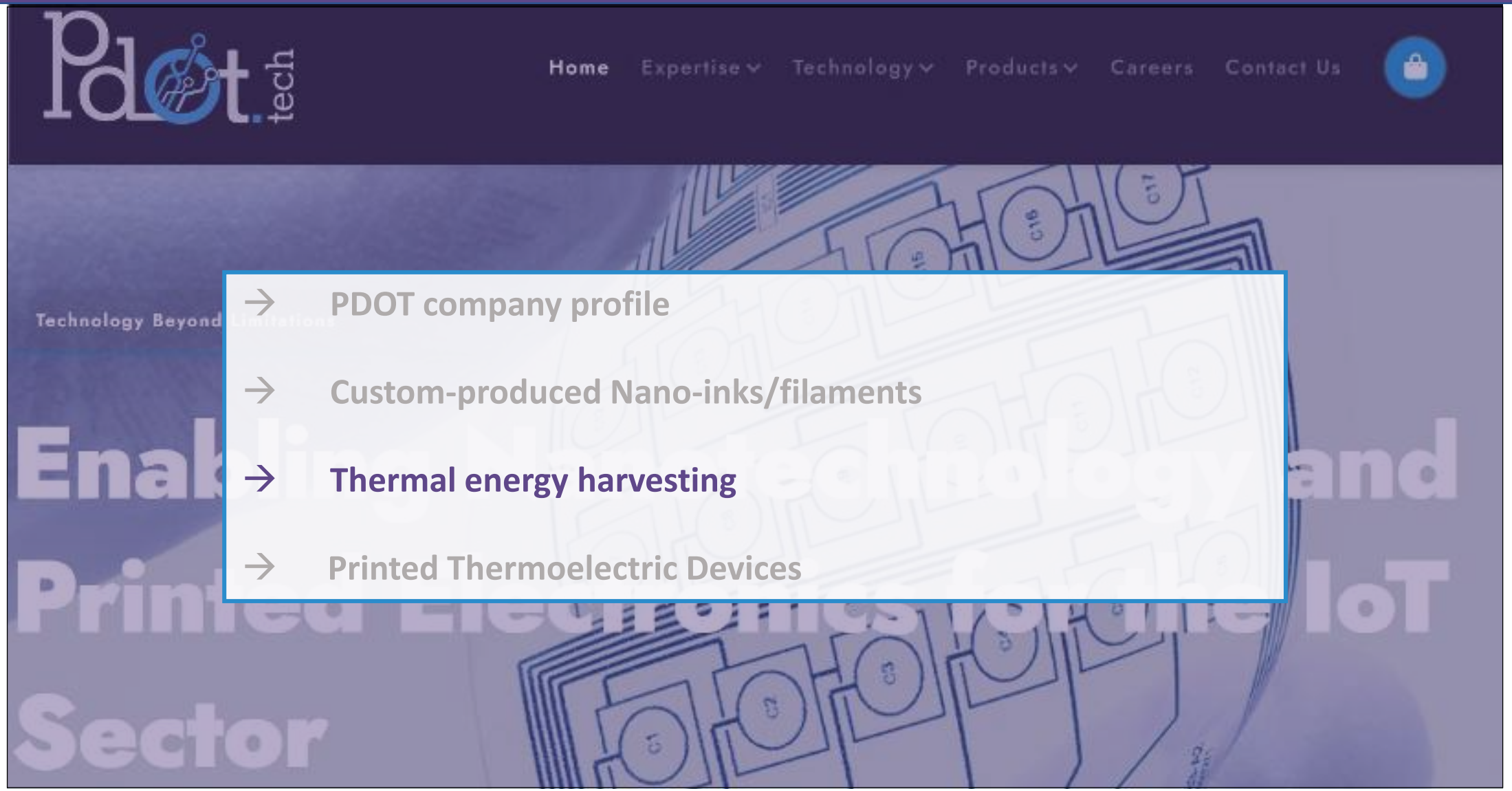
- ✓ low-cost
- ✓ flexible
- ✓ lightweight
- ✓ easy to connect & integrate (closest to the surface)
- ✓ low-power consumption
- ✓ fast response-& stability-uniformity

printed conductive filament-based strain gauge sensors

Key features of Printed Strain gauge Sensors include:

- ✓ low-cost
- ✓ thin-flexible-stretchable
- ✓ lightweight
- ✓ easy to connect & integrate
- ✓ highly sensitive

Outline



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- → Printed Thermoelectric Devices

Converting Temperature Difference into Voltage

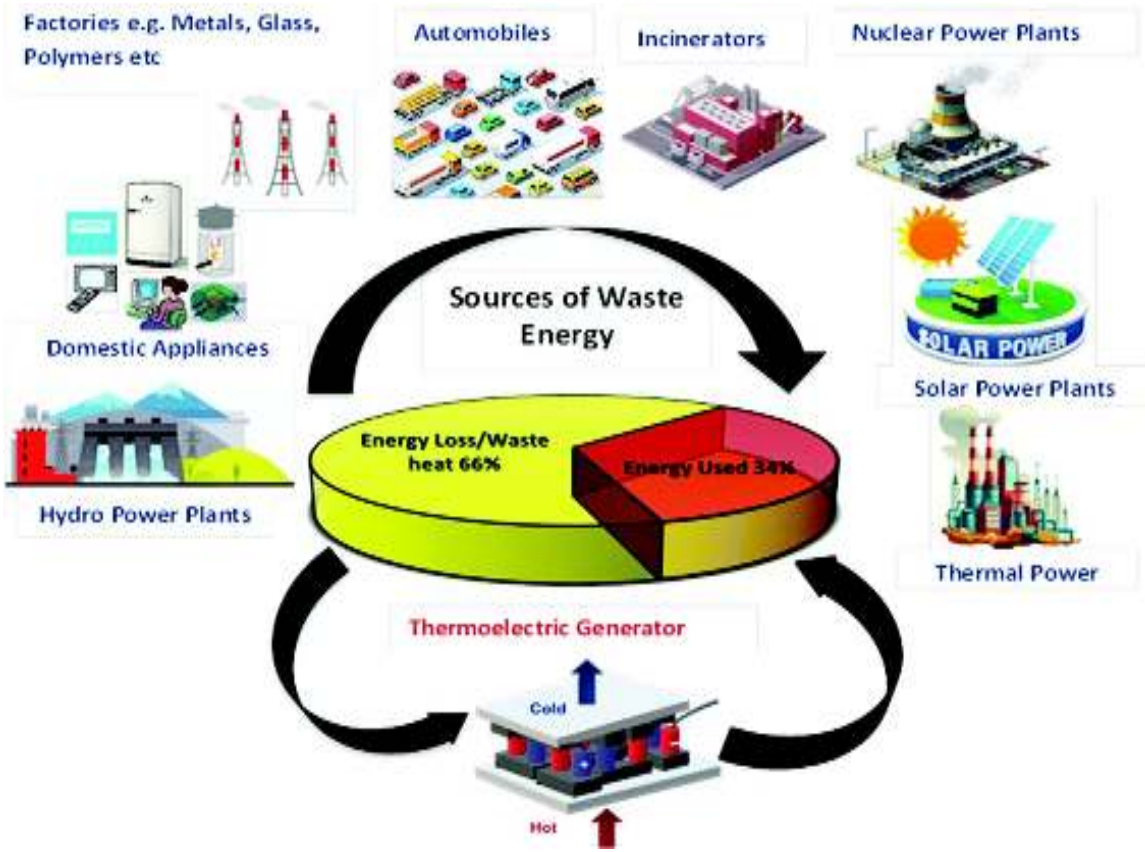
(waste heat to power the next generation of **IoT** devices and renewable energy infrastructure)

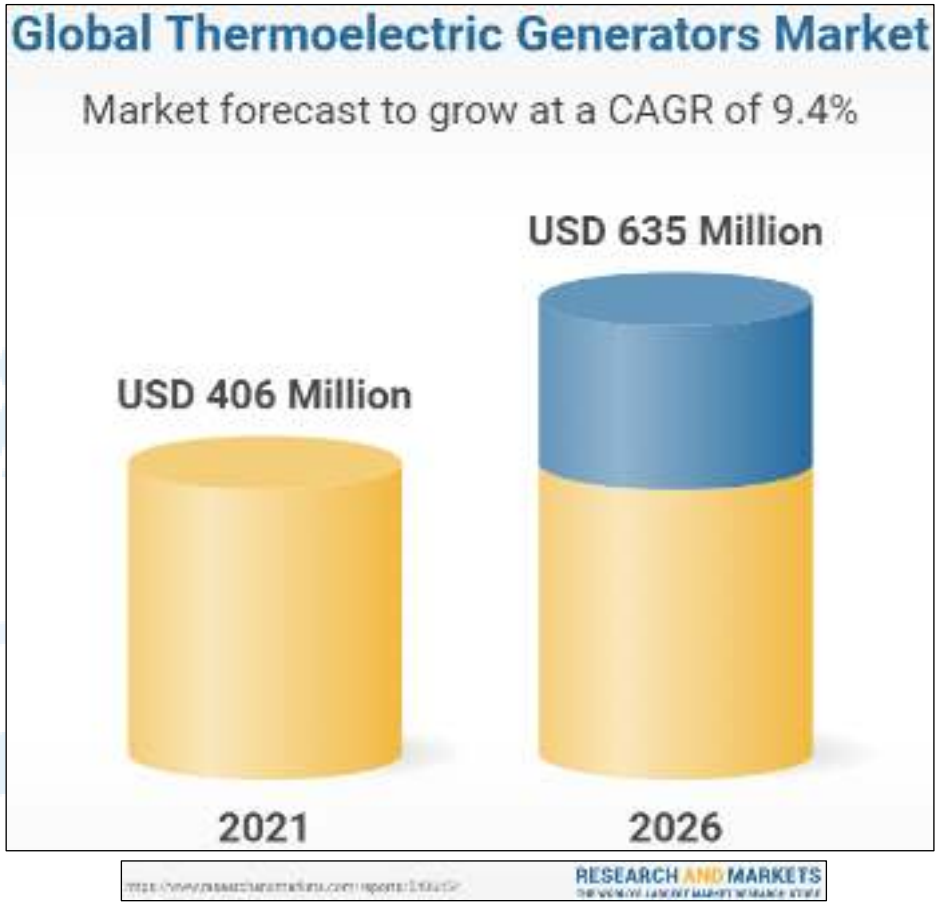
<u>Demand</u> for power supply alternatives for battery-driven sensors ..

98% of businesses report that a single hour of interruption affects their productivity, costing them more than **100K €**
(Production *downtime* due to battery change..)

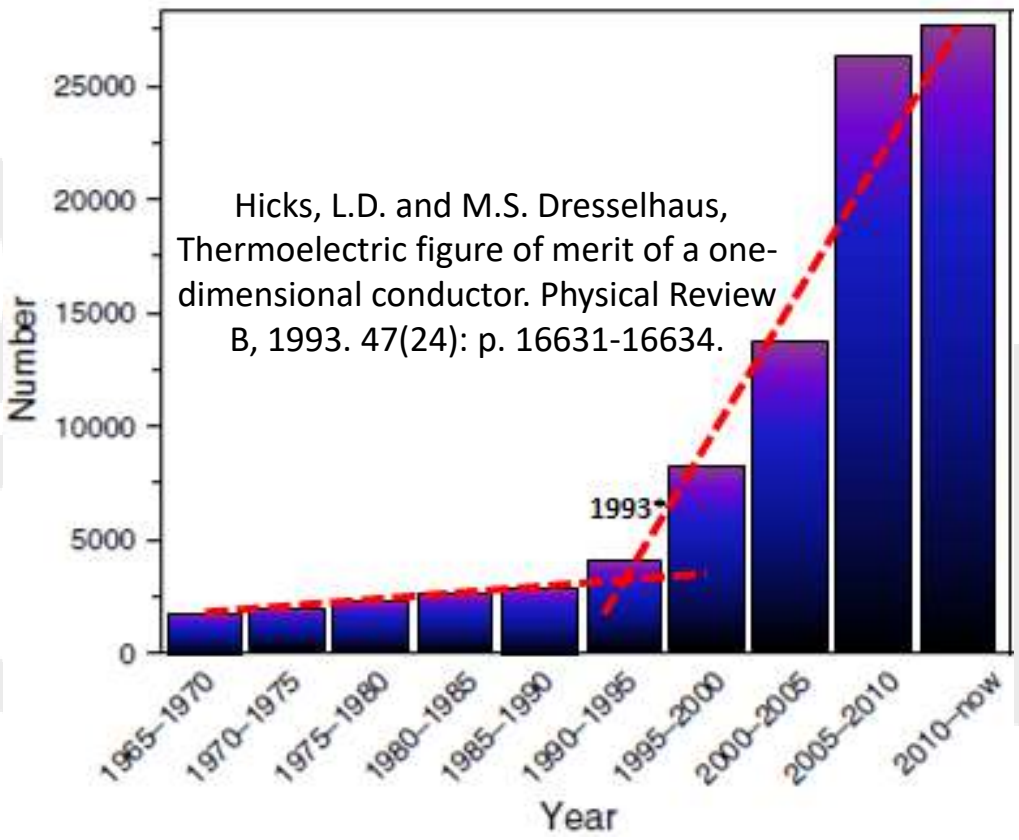
Thermal energy harvesting

→ Existing problem identification



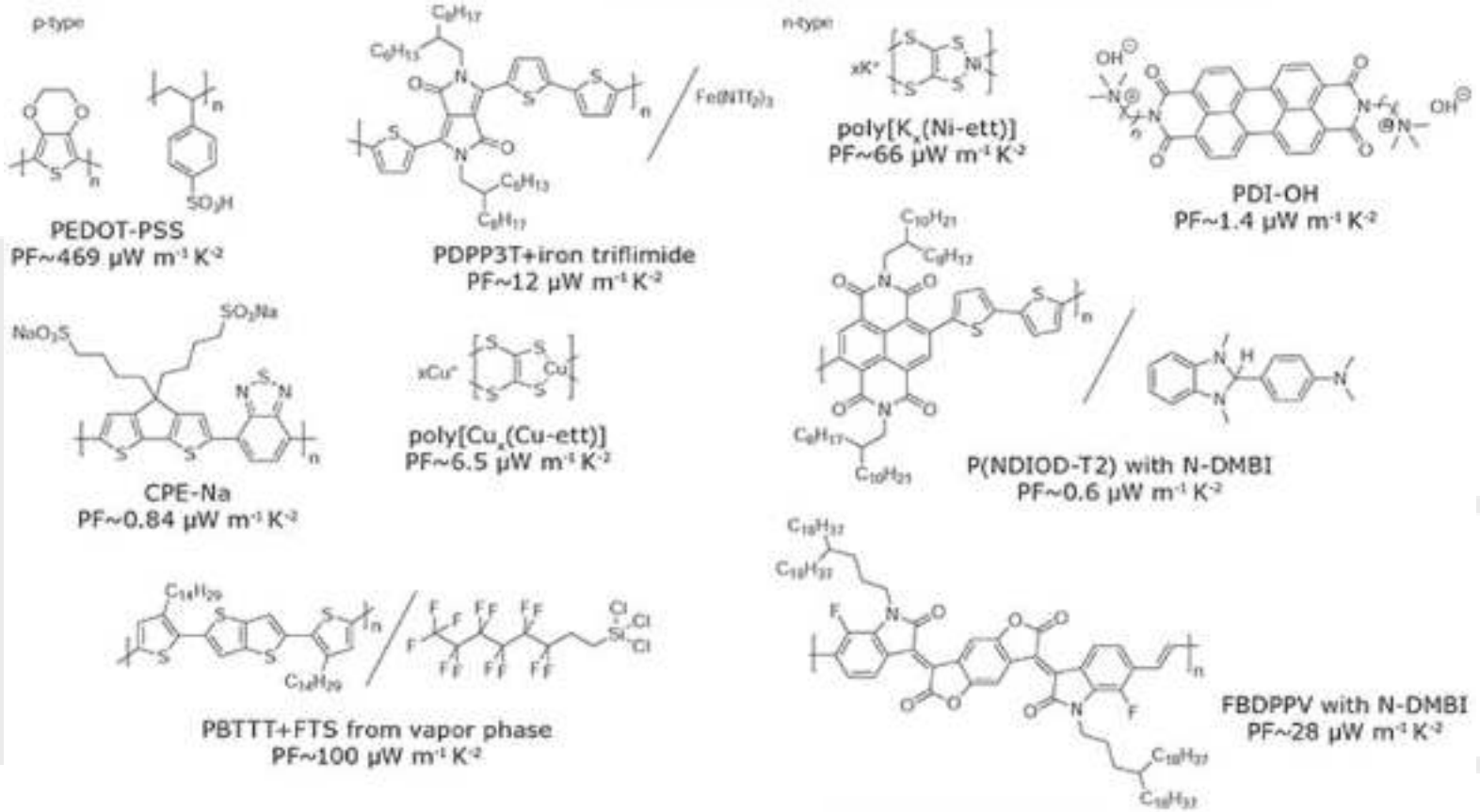


→ Number of publications in the area of TE materials & related technology from 1965 till today ..



Hicks, L.D. and M.S. Dresselhaus, Thermoelectric figure of merit of a one-dimensional conductor. Physical Review B, 1993. 47(24): p. 16631-16634.

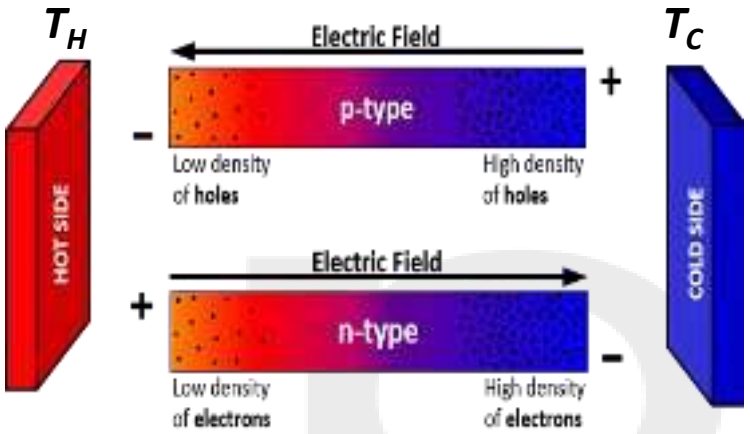
→ Representative p-type & n-type semiconducting polymers/dopants materials (respective power factors)



Organic TE Materials.. from 2003 the first publications.. (Conjugated polymers) NOT STABLE @ high ΔT

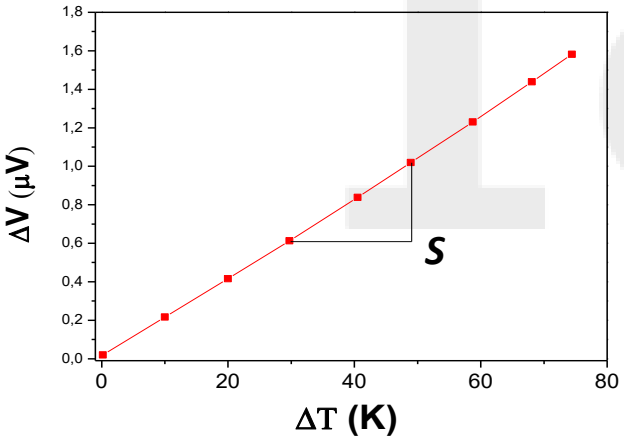
The **future might be Carbon allotropes** (carbon fibers, CNTs, graphene, etc.)

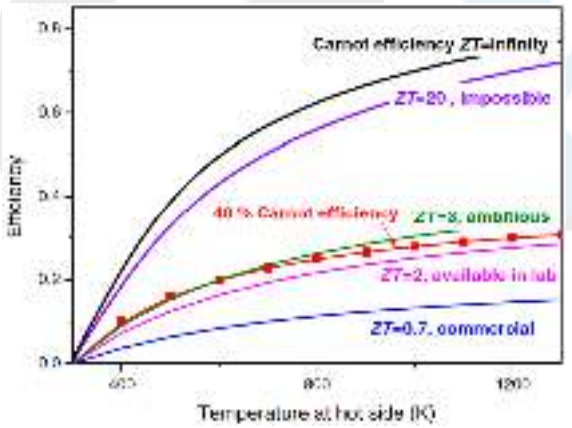
➢ **T. Seebeck (1821)**: direct temperature difference (**Δ*T***) conversion of semi-conductors to electric potential (**Δ*V***)



Seebeck effect: Thermoelectric (**TE**) effect

- ✓ **Seebeck coefficient (*S*): intrinsic-physical material property**
- ✓ **movement-interaction of electrons/phonons affect the properties of TE materials**
- ✓ **low band-gap (E_g) semi-conductors *e.g.* Te, Bi_2Te_3, present a variety of electronic properties [holes (h^+)/p-type or electrons (e^-)/n-type] significantly affect the Seebeck coefficient (+ or -) and the electrical conductivity, while the phononic properties (phonons) affect the thermal conductivity**





PF=$\sigma \cdot S^2$ (Power factor, μW/m · K²), **σ**: electrical conductivity $\sigma = n \cdot e \cdot \mu_e + n \cdot h \cdot \mu_h$

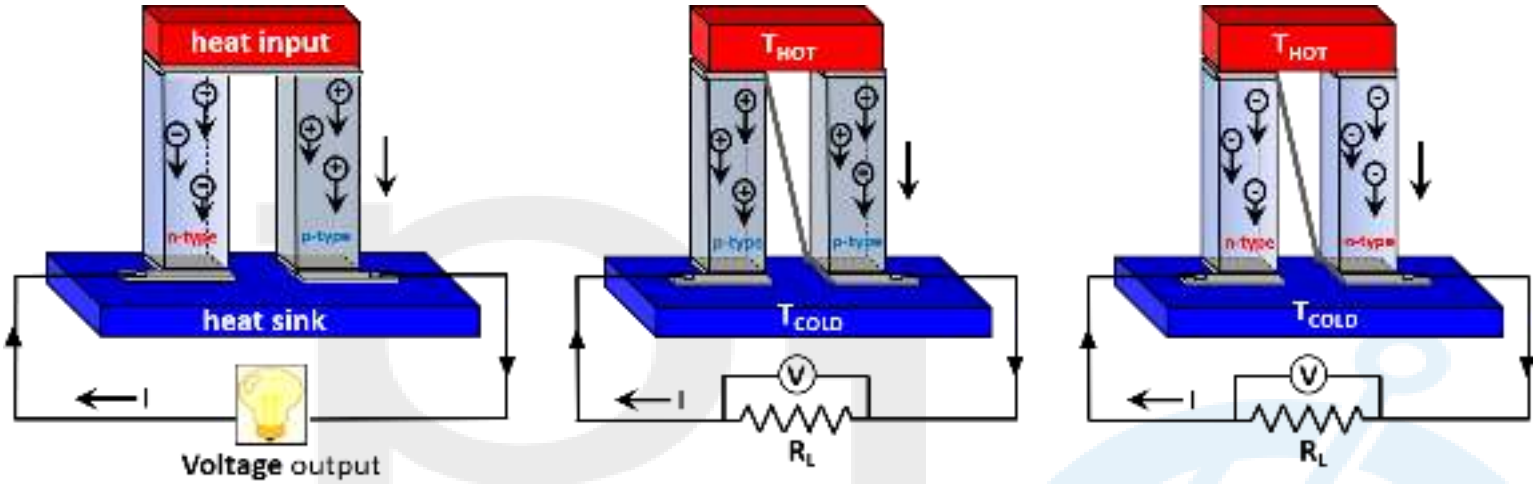
$ZT = \frac{PF}{\kappa} T$

$S = \frac{\Delta V}{\Delta T}$ (Seebeck coefficient, μV/K) $S = \frac{8\pi^2 K_B^2}{3eh^2} \cdot m^* \cdot T \cdot \left(\frac{\pi}{3n}\right)^{2/3}$

ZT=($\sigma \cdot S^2$)T/κ (ZT, **TE** figure of merit,-), **κ**: thermal conductivity $\kappa = k_l + k_e$

$\eta = \left(\frac{T_H - T_C}{T_H}\right) \frac{\sqrt{1+Z\overline{T}} - 1}{\sqrt{1+Z\overline{T}} + (T_C/T_H)}$ **η**: Carnot efficiency → thermal to electrical energy conversion

➢ **TE generators (TEGs) exploit** heat waste for electrical power (**P_{max}**) generation



TEG *assembly* { thermally in *parallel*; electrically in series }

$$P_{max} = \frac{(N\ S\ \Delta T)^2}{4R_0} = \frac{\Delta V^2}{4R_0}$$

P_{max}: maximum output of electrical power
N: number of thermocouples/thermoelements
R_0: internal electrical resistance of the **TEG** (R_{TEG})

$$P_{density} = \frac{P_{max}}{N \cdot A}$$

$P_{density}$: thermoelectric power density
N: number of thermoelements
A: area of each thermoelement

✓ **multiple interconnected thermoelements consist module-units of TEGs**

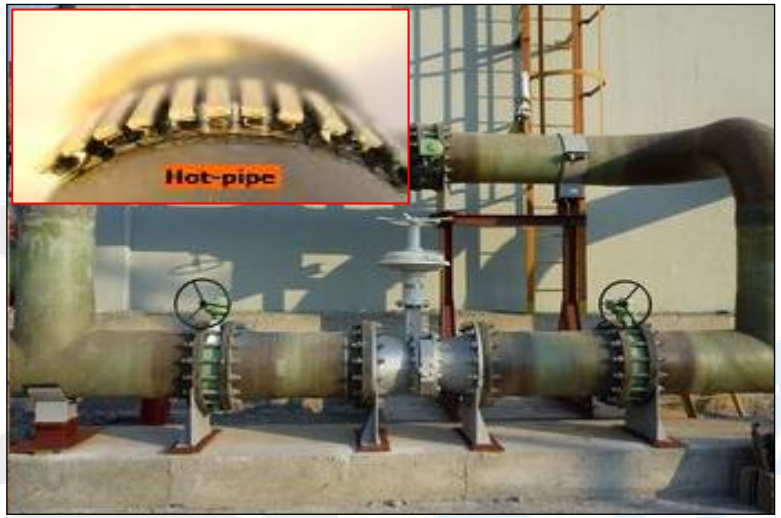
✓ **consisting of από semi-conductor thermocouples (p-/n-) or (p-/p- & n-/n-)**

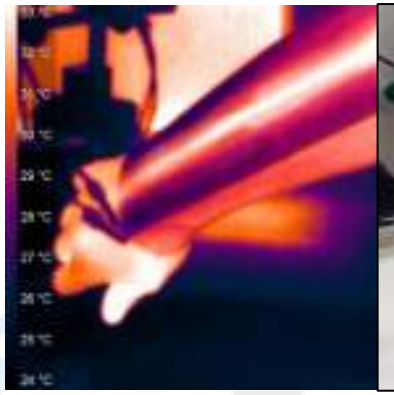
ZT=1 Power Conversion Efficiency (**PCE**) of *conventional* inorganic-based **TEG**s is **~5–8%**

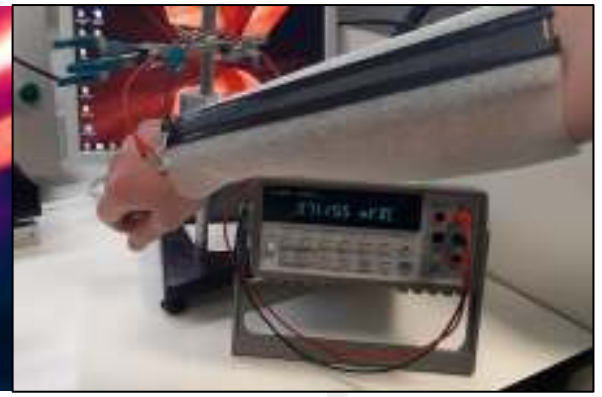
ZT=0.5 Power Conversion Efficiency (**PCE**) of *novel* organic-based **TEG**s is **~2–6%**

Thermal energy harvesting

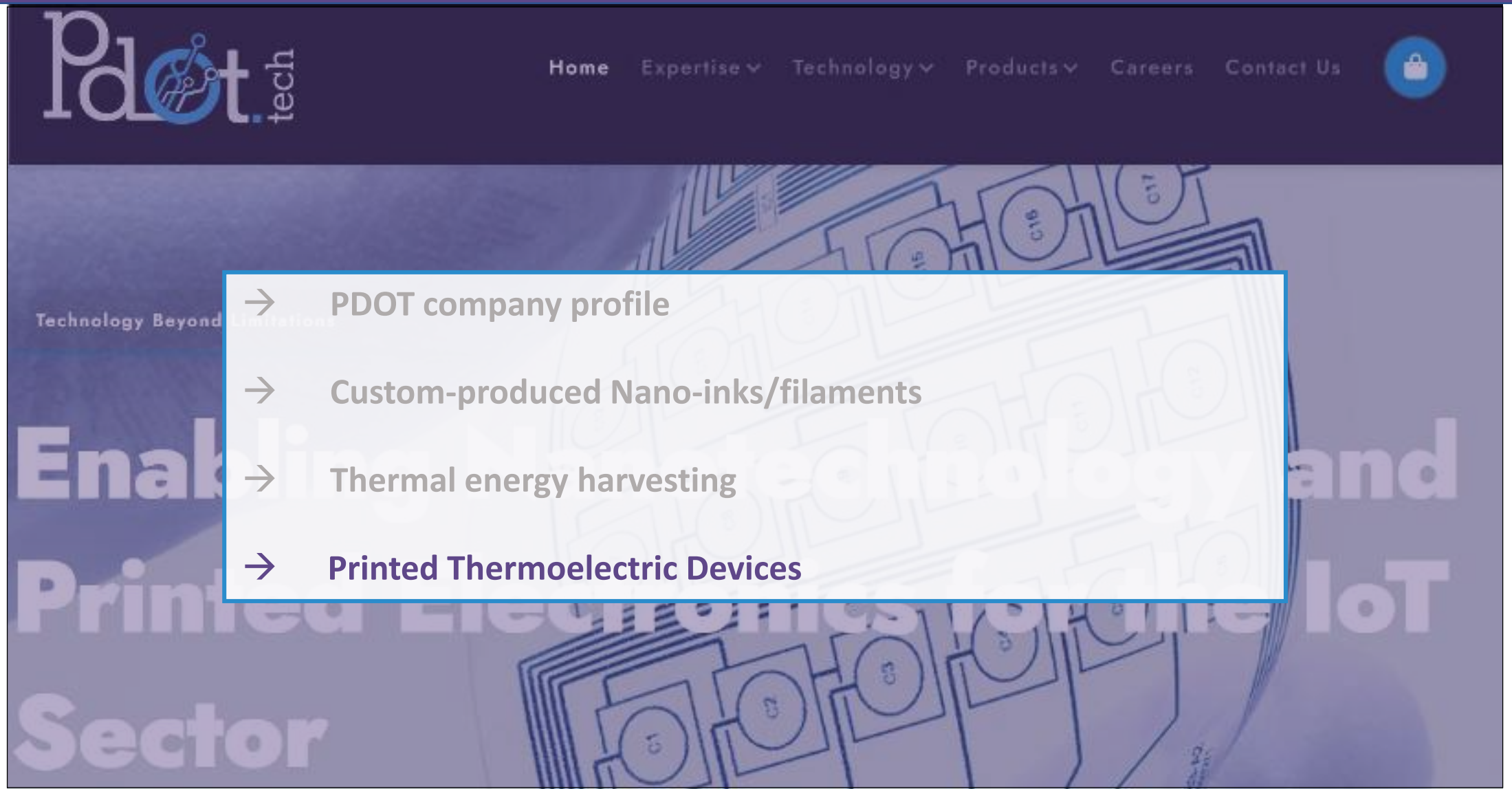
conventional TEGs → **state-of-the-art TEGs**







Outline



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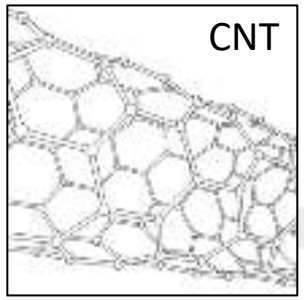
aqueous CNT Nanoinks with tailorable electronic properties



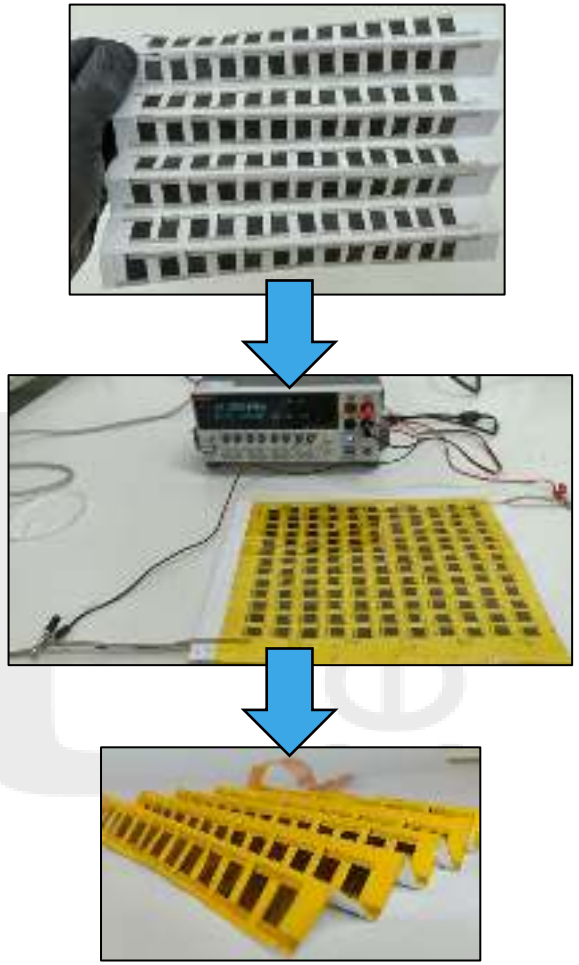
CNT powder

p- & n-type CNT-based aqueous inks/pastes

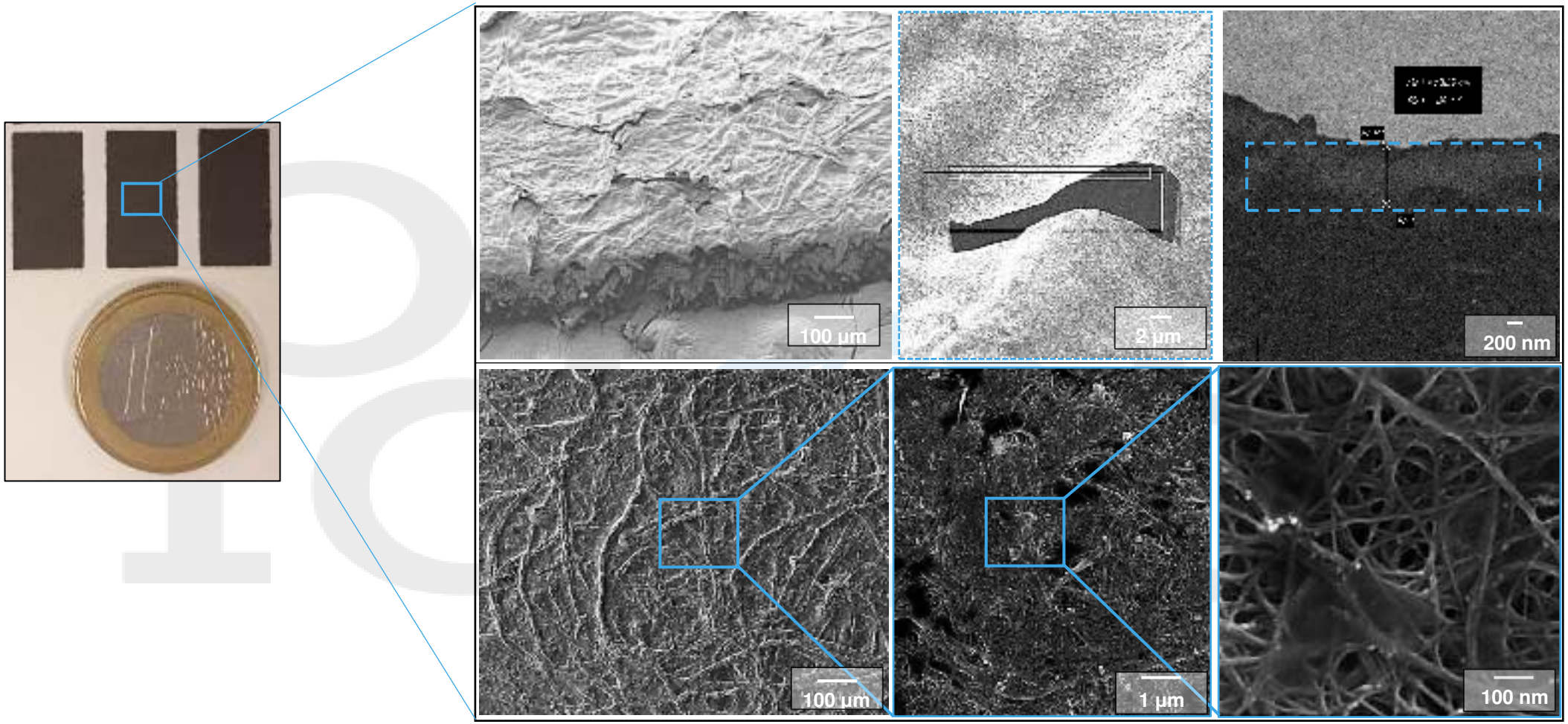
Key features of Printed TE fims include:

- ✓ low-cost
- ✓ flexible
- ✓ lightweight
- ✓ highly conductive (10^5 S/m)
- ✓ highly stable electronic properties
- ✓ superior TE efficiency

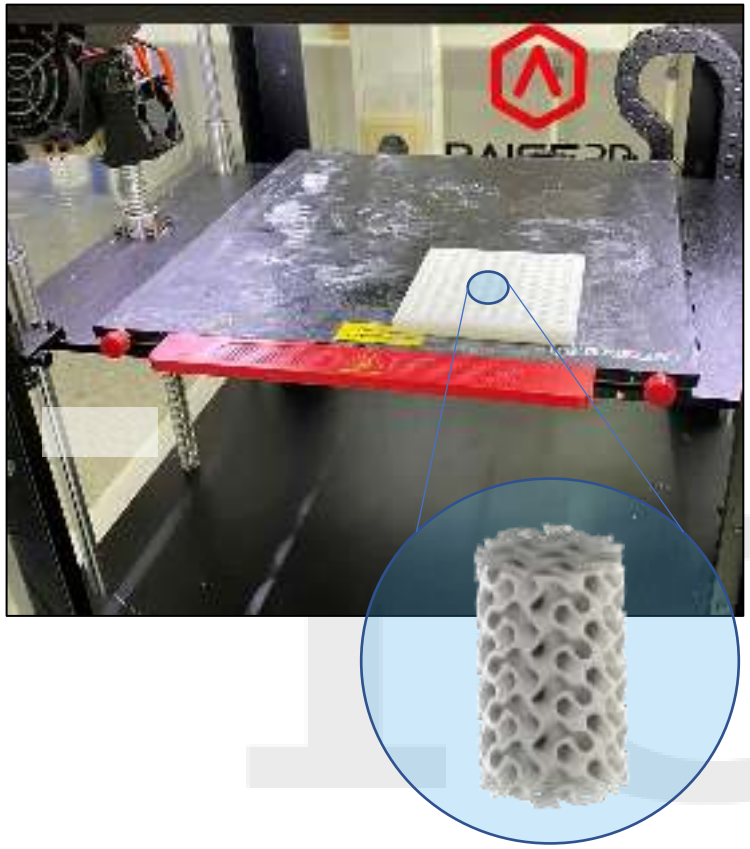
2D printing of Thermoelectric generator foldable Device



2D printing of Thermoelectric generator foldable Device



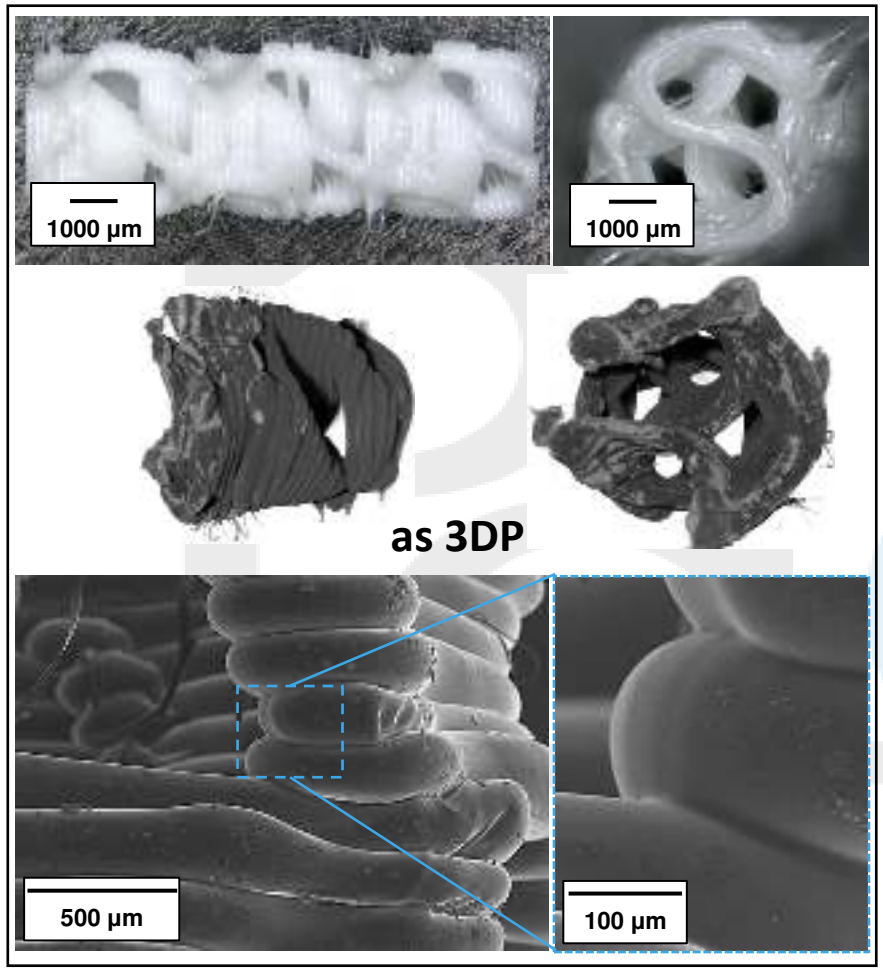
3D printed host-scaffold porous structures for functional Nanoinks

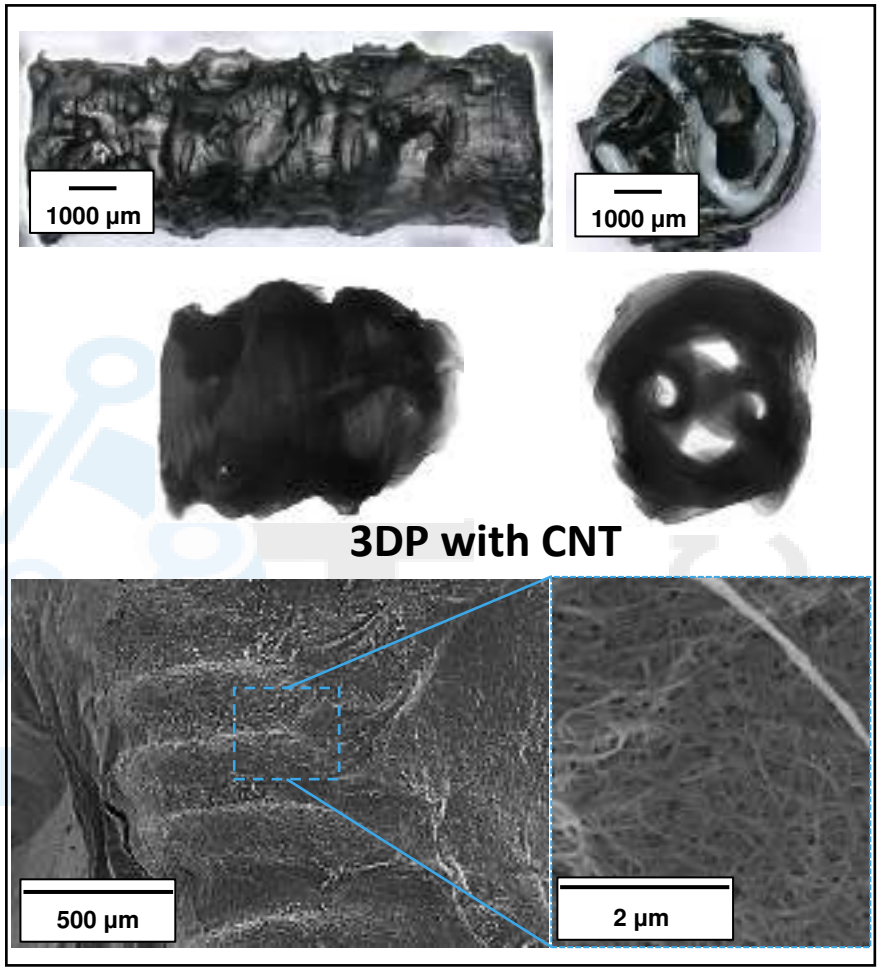


as 3DP

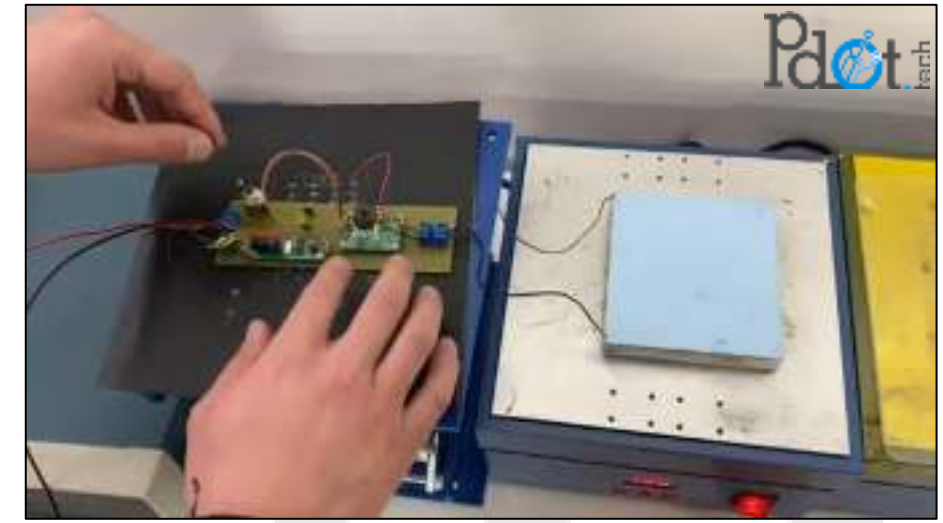
3DP with CNT

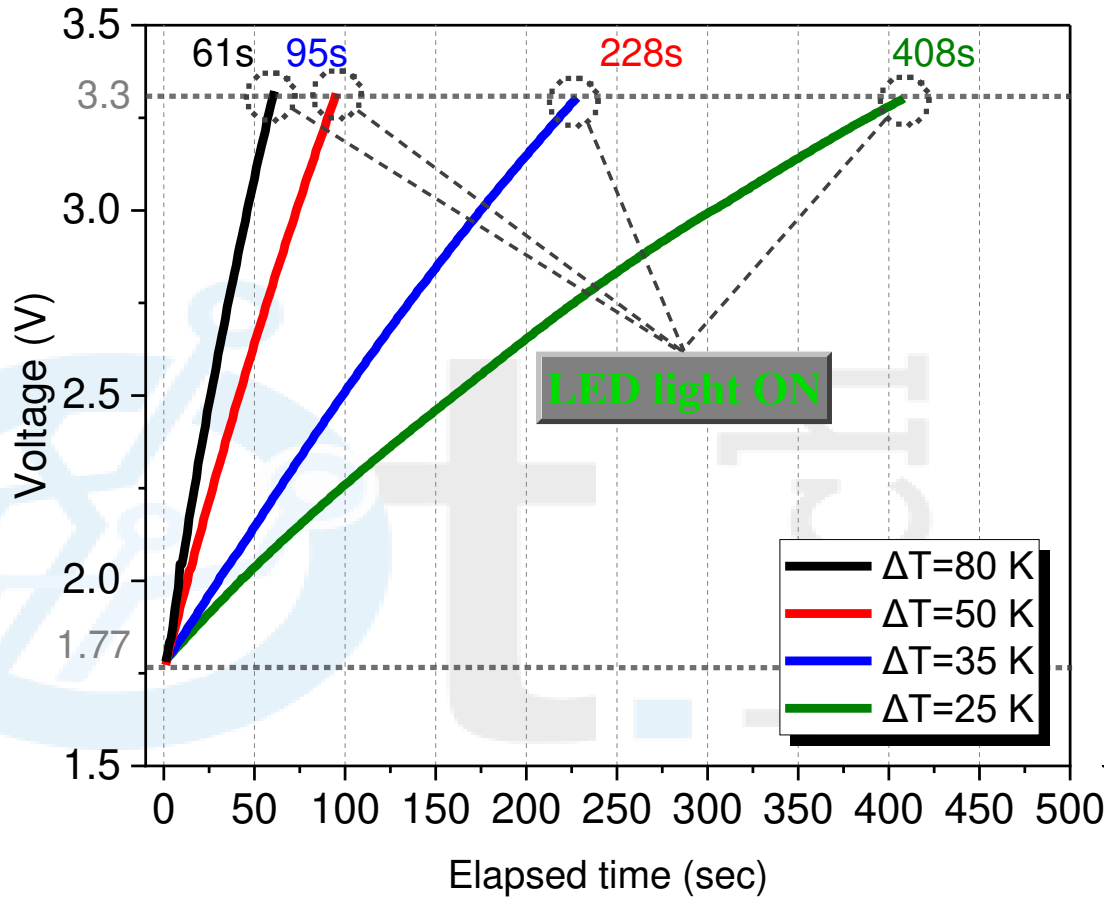
3D printed host-scaffold structures for functional Nanoinks



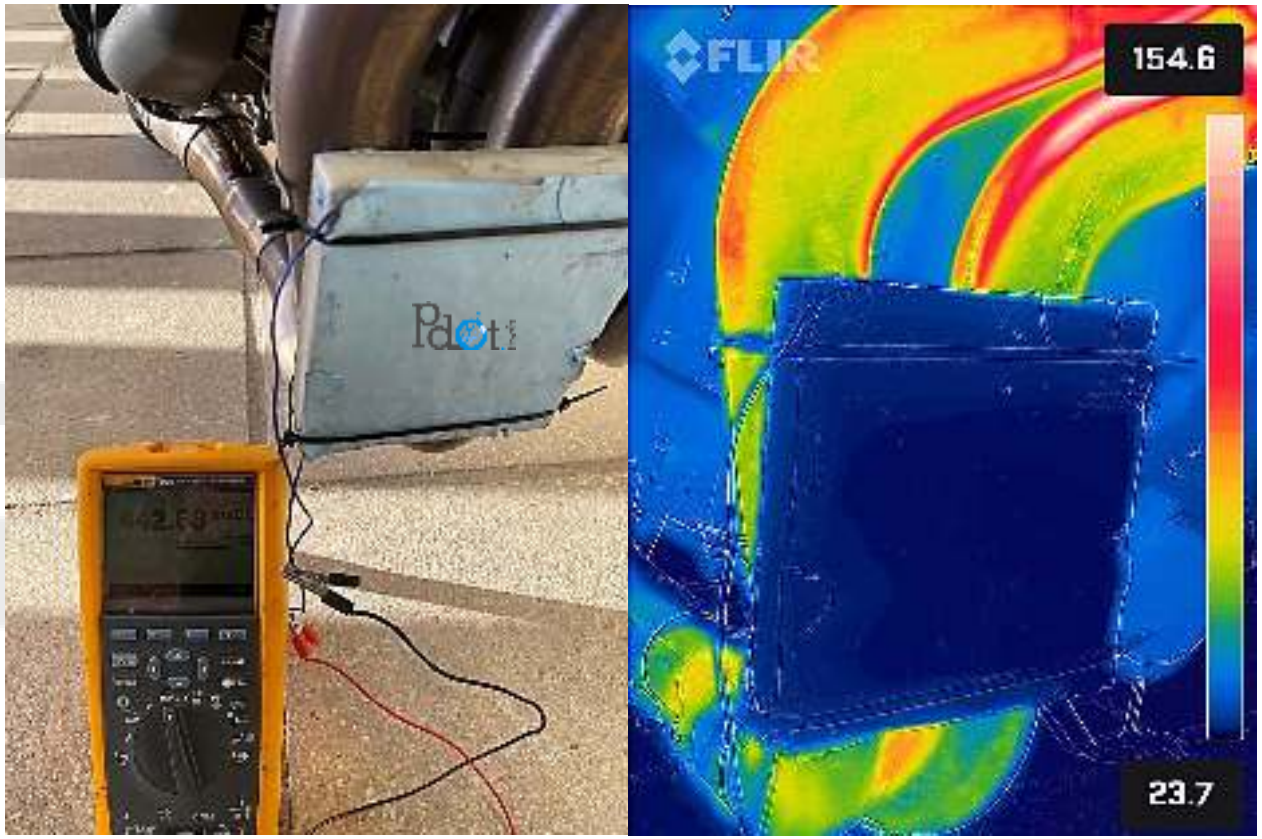


exploitable Power generation





field application



Thank you for your attention!

Any questions ?

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