Energy Harvesting Technologies for Road Pavements

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Università di Napoli Parthenope

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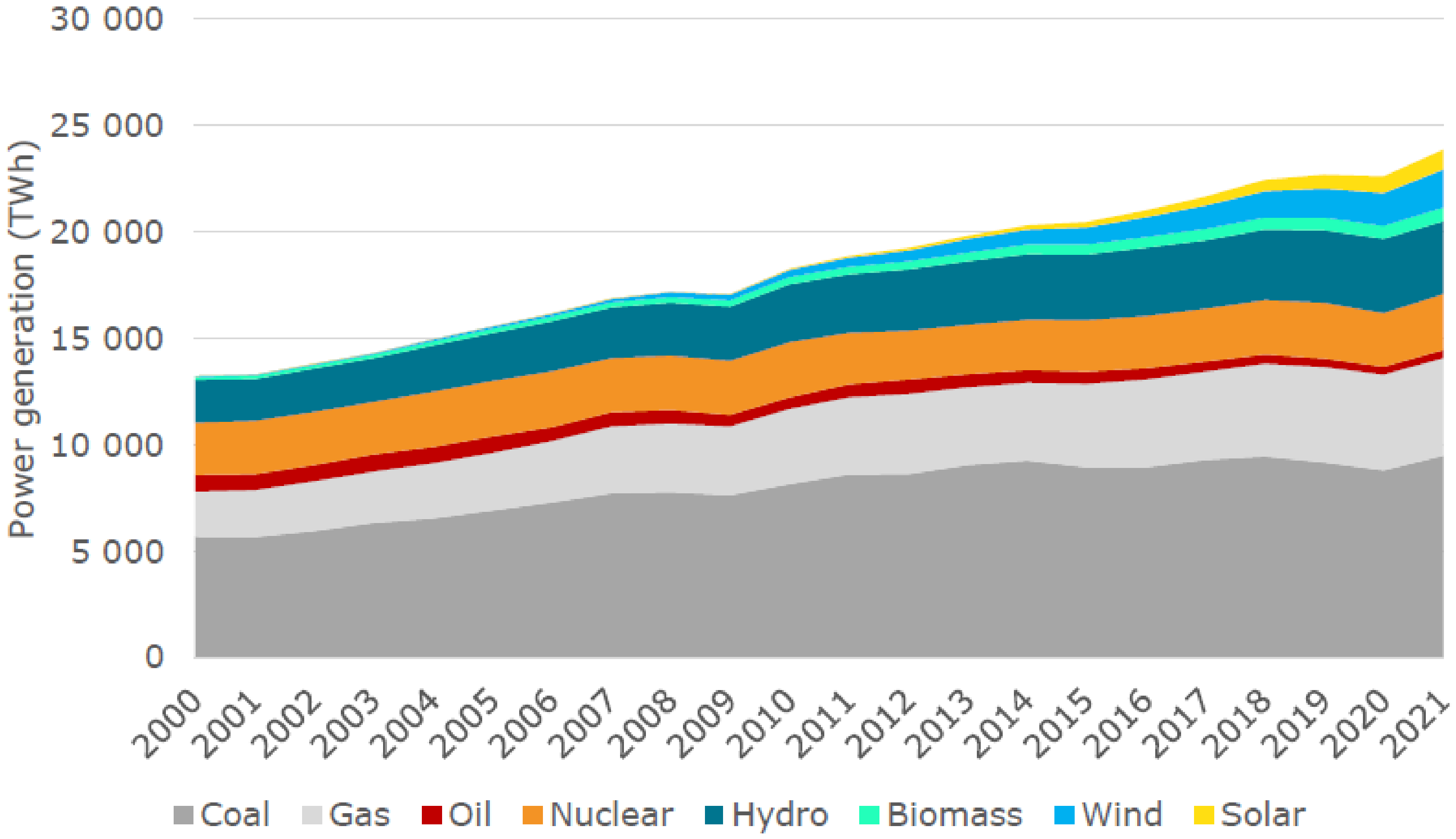
Outline

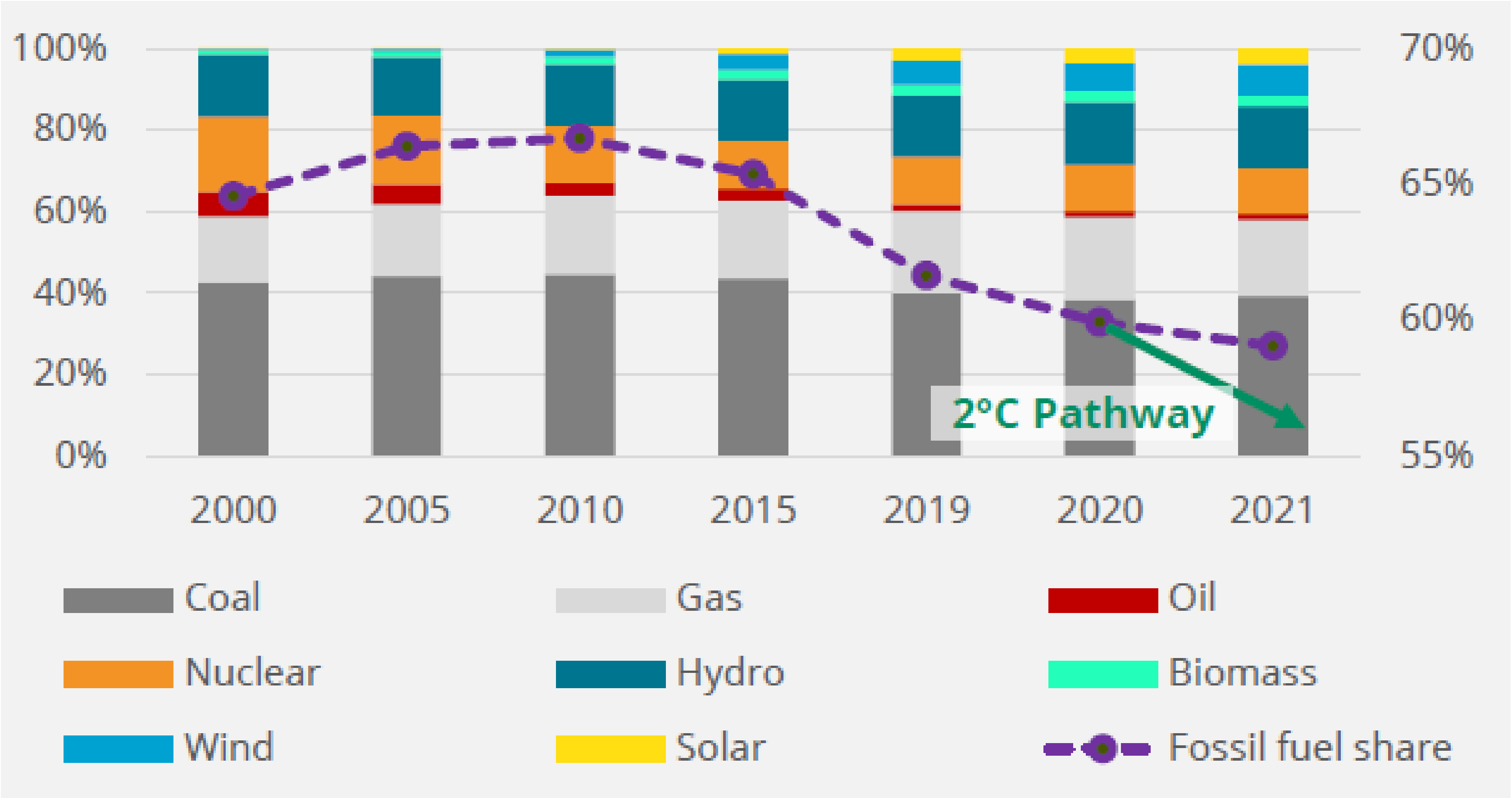
- The general context
- Heat transfer mechanisms in pavements and thermo-physical properties of pavement materials
- Available energy harvesting technologies
  - Solar Energy
  - Thermal Energy
  - Mechanical Energy
- Comparison of Technologies
- Conclusion

Evolution of power generation by source - G20



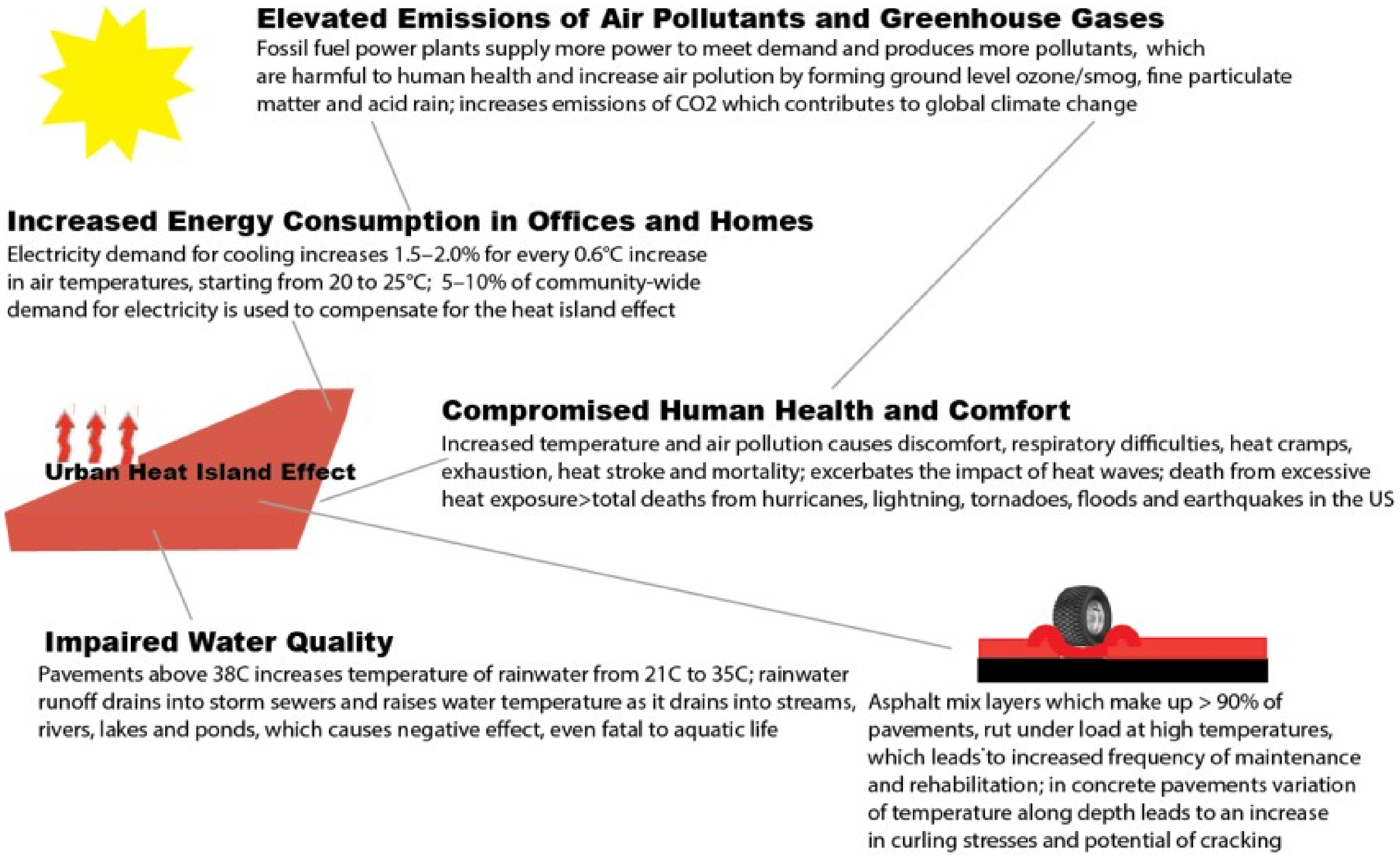
Source:
Enerdata, 2022

Evolution of power generation by source - G20



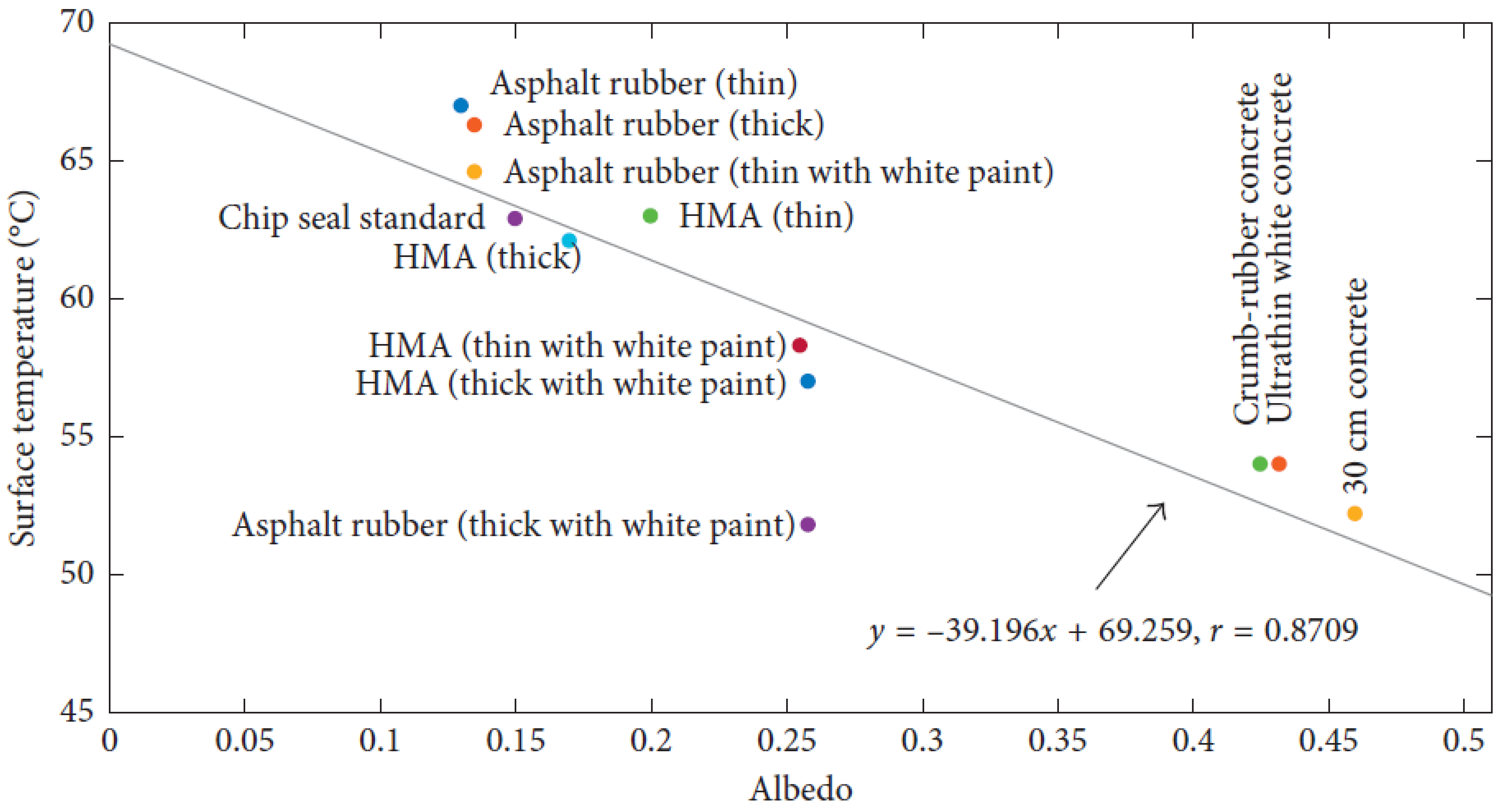
Source: Enerdata, 2022

Effects of high temperatures on pavements



Source:
A Dawson et al. (2014). “Energy Harvesting from Pavements”, published in Climate Change, Energy, Sustainability and Pavements, Springer

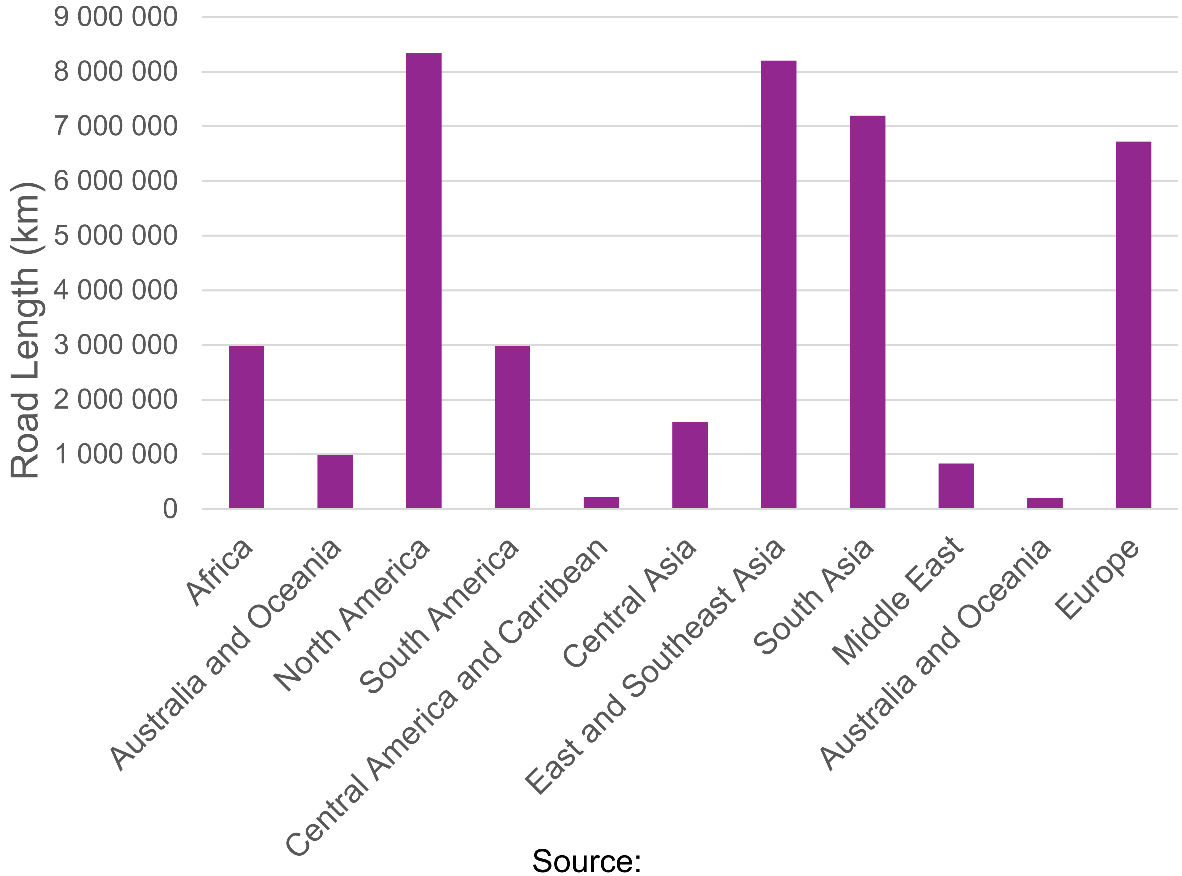
Albedo of pavement surface



Source: W.Sun et al. (2018). "The State of the Art: Application of Green Technology in Sustainable Pavement", Advances in Materials Science and Civil Engineering, Vol. 2018

Road network length and surface

- The total road network length > 40 mill. km
- Advantage - already built roadways can be used - no additional land area required



Source: https://www.cia.gov/the-world-factbook/field/roadways/country-comparison, accessed 01.09.2022

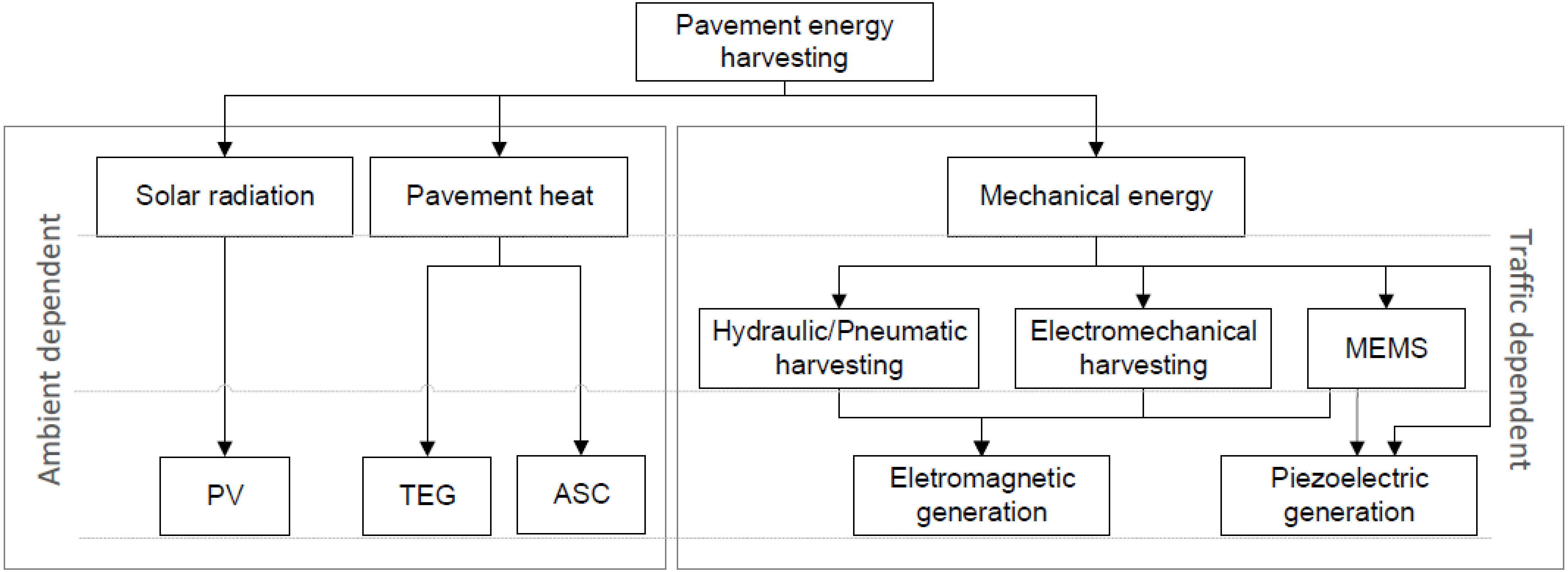
Sources of renewable energy

- Typical sources of renewable energy:
  - Solar radiation
  - Geothermal heat
  - Vibrations due to hydro, wind, wave and mechanical load.
- Pavements are exposed to:
  - Solar radiation
  - Geothermal heat
  - Traffic-induced loading
- **Good opportunity to harvest renewable energy from pavements!**

Multiple potential applications of harvested energy

- Powering:
  - pavement and structural health monitoring devices,
  - road-side or traffic lights,
  - infrastructure sensors, and
  - near-field communication systems
- Storing heat for later use for specific applications (e.g. de-icing)
- Potential surface cooling – to some extent mitigates UHI effect (particularly important in hot climates)
- Marginal reduction in operating temperature of AC surface – improvement of rut resistance

Energy Harvesting options for pavements



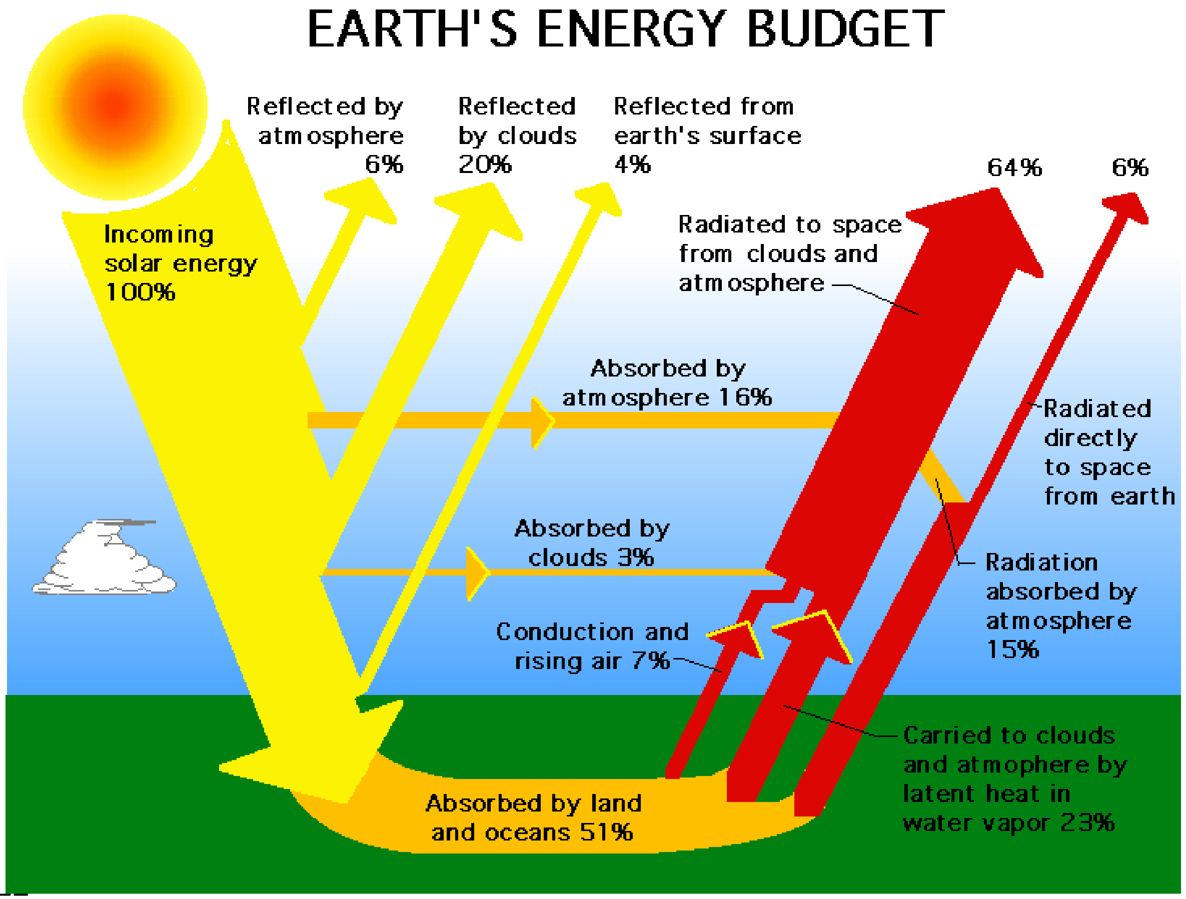
Source:
Correia, D. & Ferreira, A. (2021). "Energy Harvesting on Airport Pavements: State-of-the-Art". Sustainability, 13, 5893.

Solar radiation

- Half of the world's incoming solar energy is absorbed by the earth's surface
- Solar energy is provided to earth's surface at a rate of about 100.000 TW, i.e. the energy from one hour of sunlight is approximately equivalent to all the energy mankind currently uses in a year.

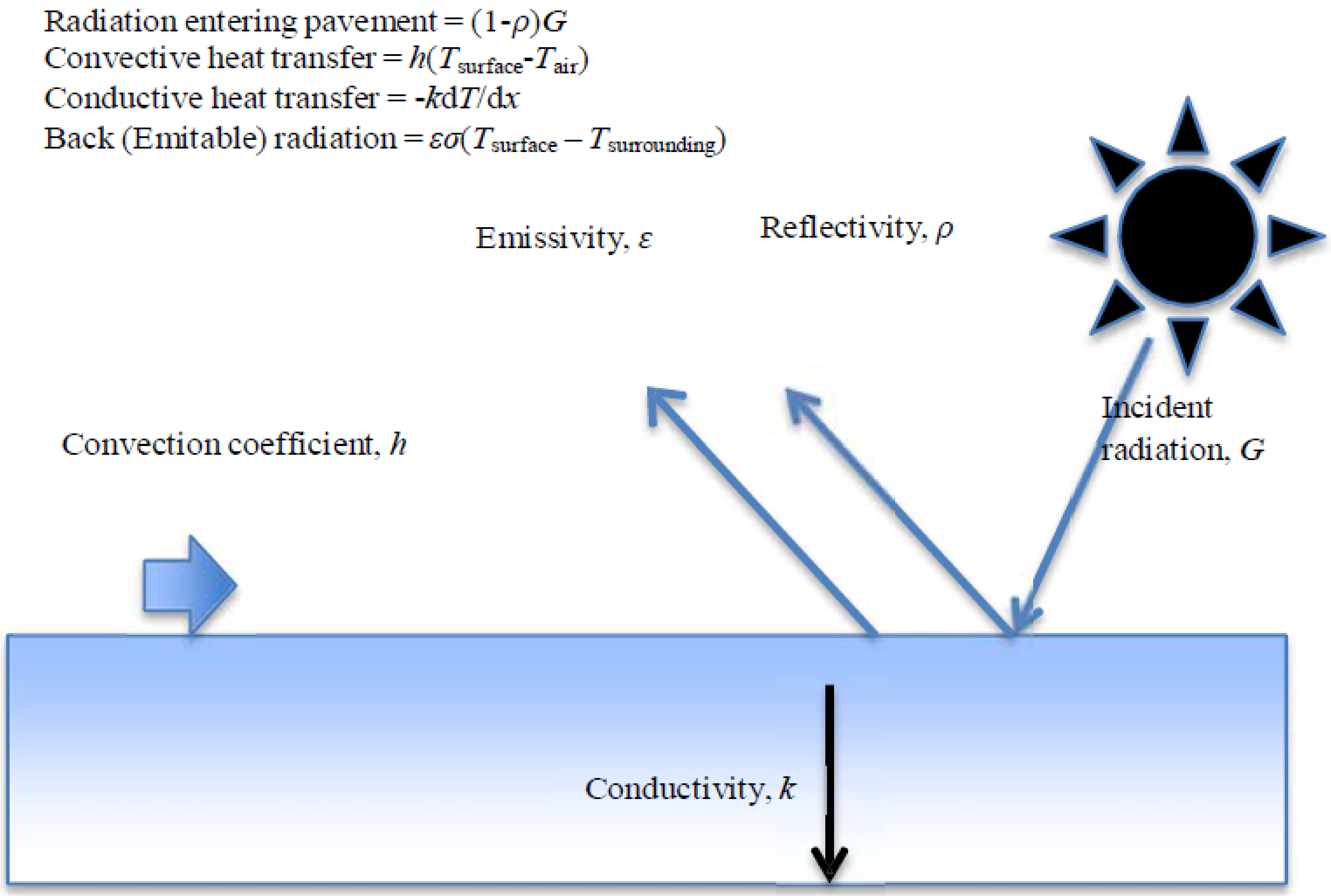
Energy balance in pavements

- The energy balance in pavements involves five factors:
  - Solar radiation (irradiance)
  - Absorption and reflection
  - Conduction
  - Convection, and
  - Thermal radiation



Source: NASA

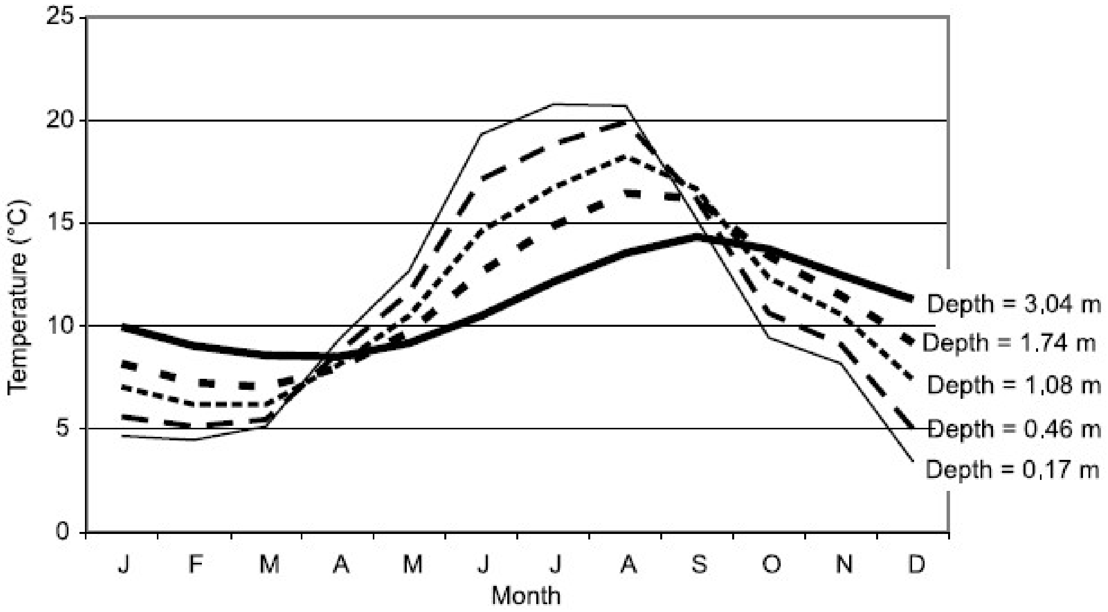
Heat transfer mechanisms in pavements



Source:
A Dawson et al. (2014). "Energy Harvesting from Pavements", published in Climate Change, Energy, Sustainability and Pavements, Springer

Energy characteristics of pavement materials

- The temperature of pavement surface increases in summer, and during the day, due to solar radiation.
- However, deeper in the pavement structure temperature is quite stable.



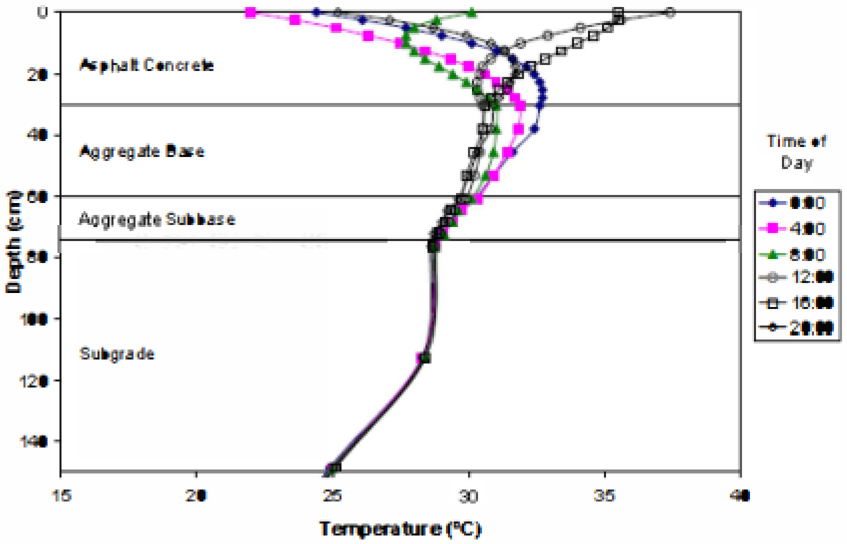


FIG. 1 Example measured daily temperature variations under pavement (Ongel and Harvey 2004 [3])

Heat transfer by conduction

- The principal method of heat transfer in solid
- Can be described by Fourier's law for one-dimensional flow (which is reasonable approximation for downward heat flow in pavement):

$$Q_{conduction} = \lambda \cdot A \cdot \frac{T_1 - T_2}{\Delta x} = - \lambda \cdot A \cdot \frac{\Delta T}{\Delta x}$$

where:

$Q_{convection}$- Rate of heat conduction (W)

A – Surface area (m^2)

λ – Thermal conductivity of material (W/m ^oC)

ΔT / Δx – Temperature gradient in the direction of heat flow ($^oC/m$)

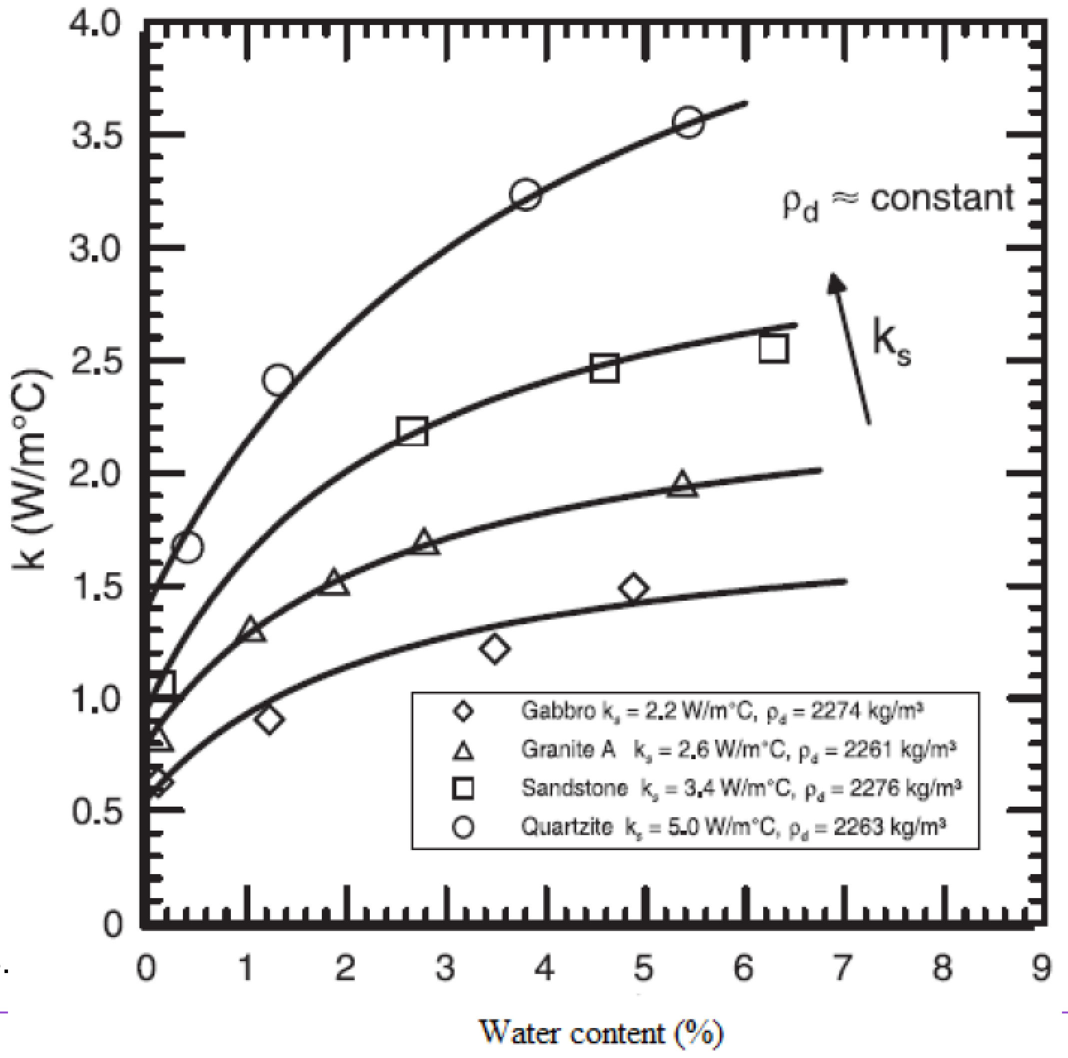
Dry thermal conductivity of pavement materials

Constituent	Range of thermal conductivity λ (W/m/°C)
Quartzite	**5.5 – 7.5**
Granite	3.0 – 4.0
Limestone	1.5 – 3.0
Basalt	1.3 – 2.3
Cooper Slag	2.2
Lightweight aggregate	1.0
Bitumen	0.15 – 0.17
Cement	0.29
Water	0.6
Air	0.024

Source:
A Dawson et al. (2014). "Energy Harvesting from Pavements", published in Climate Change, Energy, Sustainability and Pavements, Springer

Thermal conductivity of pavement materials

- Thermal conductivity of layer (k) depends on thermal conductivity of solid particles (k_s)



Source:
Côté, J. & J.M. Konrad (2005). "Thermal conductivity of base-course materials", Canadian Geotechnical Journal, 42(1): 61-78.

Ability of pavement materials to store energy

- **The specific heat capacity** – main property affecting a material's ability to store energy
- Defined as the energy required to raise the temperature of a unit mass of a substance by one degree

$$\boldsymbol{\Delta}\ \boldsymbol{Q} = m \cdot \boldsymbol{C_p} \cdot \Delta T$$

where:

ΔQ – Heat energy taken in or given out (J)

m – Mass (kg)

C_p – Specific heat capacity (J/kg °C)

ΔT – Temperature change caused by heat energy in/out (°C)

Specific heat capacity of pavement components

Pavement component	Specific Heat Capacity C_p (J/kg/°C)							
	-10 °C	-0 °C	7 °C	17 °C	27 °C	37 °C	47 °C	57 °C
Limestone	793	838	859	878	892	904	917	931
Quatzite	609	629	642	659	675	693	709	724
Cooper slag	628	670	679	691	701	712	723	734
Natural sand	610	637	655	679	698	711	721	734
Lytag (Light aggregate)	620	712	741	767	778	787	799	812
Rubber	1194	1292	1326	1369	1406	1444	1485	1523
Hardened cement paste	877	1021	1094	1241	1458	1714	1978	2300
Ferag (Steel slag)	521	552	562	575	586	589	609	618

Thermal properties of asphalt mixtures

Mix /Aggregate type	λ (W/m/°C)	C_p (J/kg/°C)	ρ (kg/m³)
Limestone (L) – control mix	1.21	919	2382
Quarztite (partial replacement of L)	1.46±0.01	880	2351
Cooper slag (partial replacement of L)	1.05±0.01	814	3088
Quartzite (full replacement of L + 2% Cu-fibre)	2.82±0.22	836	2480
Lytag (partial replacement of L)	0.46	863	1504
Alluvial gravel	1.866	1100	2276
Alluvial gravel + 10% graphite	1.983	920	2279
Alluvial gravel + 20% graphite	2.089	10	2282

Source:
A Dawson et al. (2014). “Energy Harvesting from Pavements”, published in Climate Change, Energy, Sustainability and Pavements, Springer

Thermal effusivity

- Measure of pavement material's **ability to exchange thermal energy with its surroundings** (atmosphere).

$$\mathbf{e} = \left(\lambda \cdot \rho \cdot C_p\right)^{0.5}$$

where:

e – Thermal effusivity (W $s^{0.5}/m^2$ °C)

λ – Thermal conductivity of material (W/m °C)

ρ – Density of pavement material (kg/m^3)

C_p – Specific heat capacity (J/kg °C)

Thermal diffusivity

- Measure of a pavement material's **ability to conduct thermal energy relative to its ability to store it**.

$$\alpha = \frac{\lambda}{\rho \cdot C_p}$$

where:

α – Thermal diffusivity (m^2/s)

λ – Thermal conductivity of material (W/m ^oC)

ρ – Density of pavement material (kg/m^3)

C_p – Specific heat capacity (J/kg °C)

Harvesting solar energy - Photovoltaic pavements

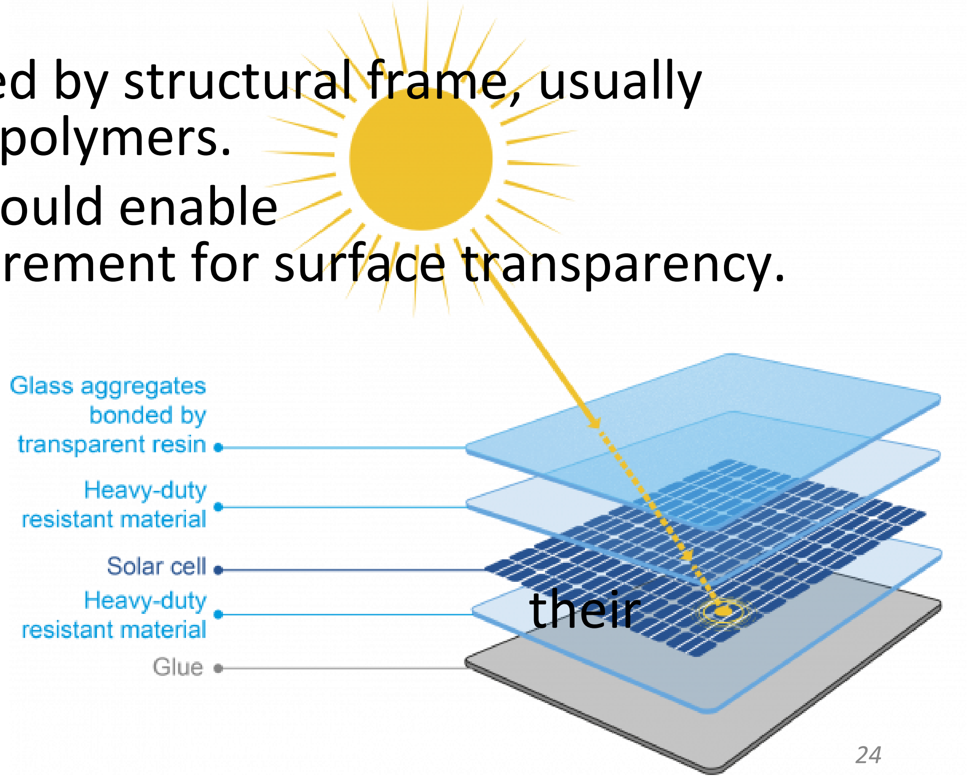
- Harvesting solar energy using PV panels that convert light into electricity is not a new concept. The efficiency of PV systems has substantially improved in the last few decades.
- Used for harvesting solar energy on noise barriers and canopies.
- The challenge is using PV panels as driving surfaces.

PV panels main considerations

- PV panels should withstand vehicle loading and weather conditions
- Major concerns are:
  - **Structural capacity** - PV panels must be supported by structural frame, usually made of steel, aluminum of fiberglass reinforced polymers.
  - **Surface friction** – need for surface texture that would enable vehicle braking. However, contradicting the requirement for surface transparency.

    Option for the transparent surface layers are:
    - Acrylic
    - Tempered glass
    - Polycarbonate

    All of which could be textured, assuming that their transparency can be maintained.



Practical applications of PV pavements

- Several pilot applications performed in recent years:
  - Solarroadways (US)
  - Colas (France)
  - Shandong (China)
  - …

Source:
https://www.extremetech.com/extreme/194313-the-netherlands-has-laid-the-worlds-first-solar-road-we-go-eyes-on-to-investigate

Practical applications of PV pavement

- Solar road in Normandy in France constructed in 2016
- L = 1 km, A = 2800 m^2
- Panels 1 m x 1 m
- Cost was about 5.2 mill. Euros/km

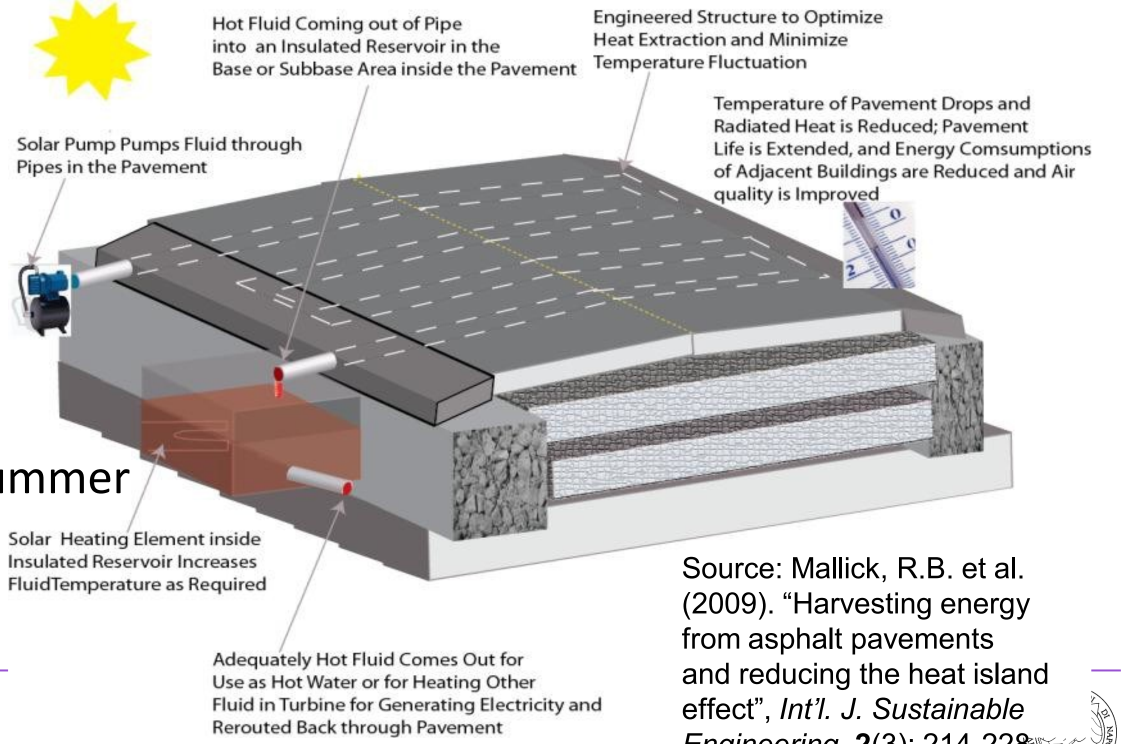
Source: https://arstechnica.com/cars/2016/12/worlds-first-solar-road-opens-in-france/

Harvesting heat energy from pavements

- Driven by differential temperature gradients between the surface and lower pavement layers
- A variety of applications that use these temperature gradients to:
  - simply store heat to be used later for specific applications (e.g. deicing)
  - drive thermoelectric generators (TEG)

Heat harvesting using liquid circulation

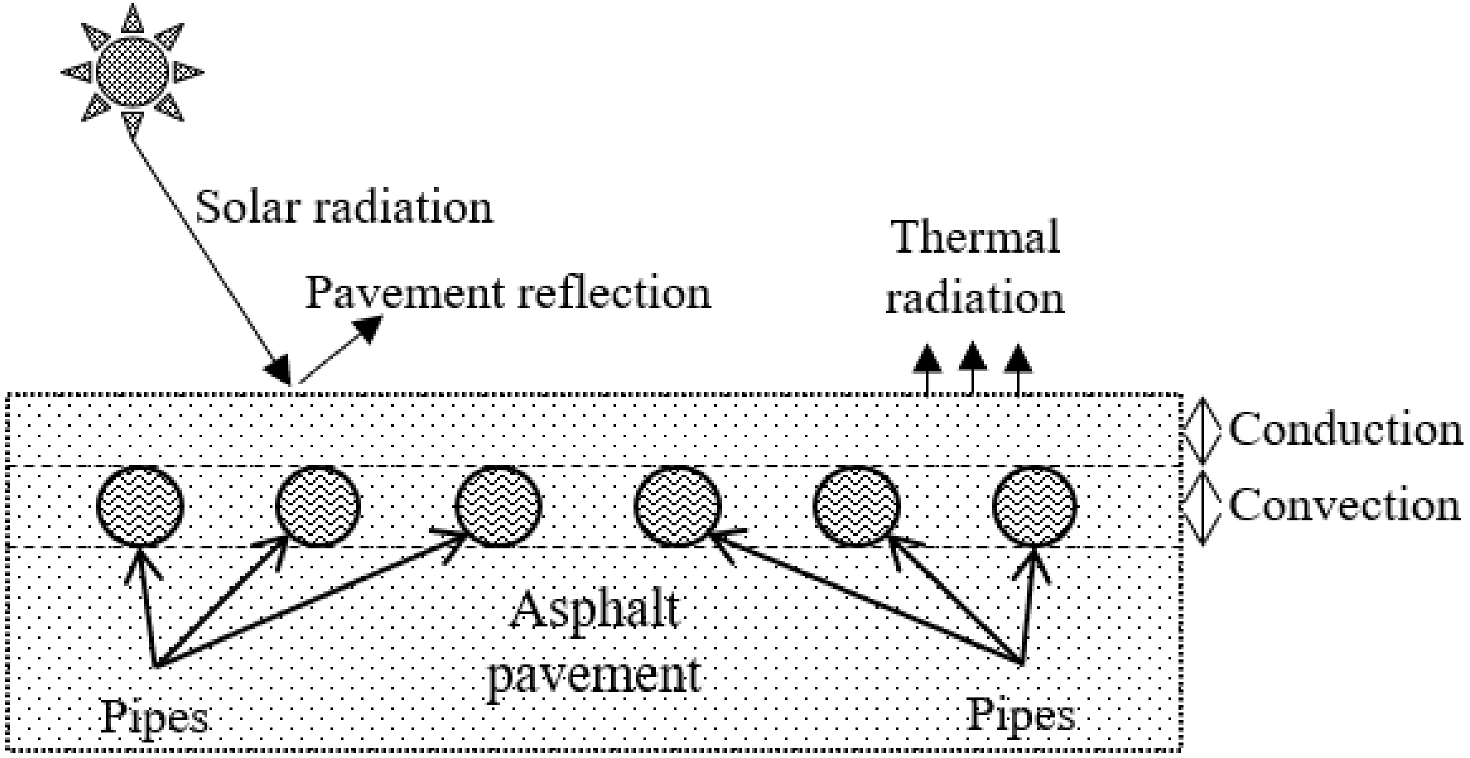
- Based on collecting and conveying heat through a network of fluid pipes embedded into pavement structure
- Water is primarily used as a fluid, although there is some research that involves air
- These systems include:
  - Asphalt solar collectors (ASC)
  - Road pavement solar collectors
  - Hydronic asphalt pavements
- Popular applications:
  - Melting snow and deicing pavement surface
  - Reducing pavement surface temperature in the summer
  - Utilizing the warm fluid to heat buildings



Source: Mallick, R.B. et al. (2009). "Harvesting energy from asphalt pavements and reducing the heat island effect", *Int'l. J. Sustainable Engineering*, **2**(3): 214-228

Heat transfer mechanism in ASC

- Based on three processes:
    - Conduction
    - Convection
    - Thermal radiation



Source:
Correia, D. & Ferreira, A. (2021). “Energy Harvesting on Airport Pavements: State-of-the-Art”. Sustainability, 13, 5893.

Asphalt Solar Collectors (ASC)

- Several factors affect the performance of ASC:
  - Ambient temperature
  - Wind speed
  - Solar radiation intensity
  - Cloud cover
  - Pavement material properties
  - Exchange system design specifics
- Pipe materials play an important role, because they control the heat transfer process. In addition, they are subjected to traffic loads and need to have sufficient strength.

ASC efficiency and applications

- Efficiency – Ratio of collected energy to the whole input solar energy
- May be cost-effective, and payback period may be as short as 10 years
- Heat collection capacity is up to 250 W/m^2
- ASC has been installed:
  - On bridges in several states in US
  - Several airport runways in Sweden, Norway and Poland
  - SERSO system in Switzerland installed in the pavement for melting snow and deicing the pavement surface.

Difficulties of pipe systems

- Pipe systems have poor access maintenance and low operational reliability.
- Even with a tiny defect in the pipe system, the pavement must be removed to repair the pipeline and then repave that spot.
- In addition, this mechanism uses water as the main operating fluid flowing through the embedded pipes. If the pipe network below the pavement surface is damaged under intensive traffic loads, the leakage occurs and leads to significant structural damages.

Thermoelectric generators (TEG)

- TEG use thermal gradient between pavement layers to generate electrical energy.
- Based on Seeback effect – electrical voltage generated between two points of an open circuit made from two heterogenous semiconductors (N-type and P-type), providing the ability for electrons to move freely through metals and semiconductors.
- This effect manifests itself as a voltage differential between the hot and cold site of a semiconductor in response to a thermal gradient.

Thermoelectric generators (TEG)

- TEG Voltage:

$$V = \alpha \cdot (T_h - T_c)$$

where

V - the voltage of the TEG,

T_h - the hot side temperature of the TEG,

T_c - the cold side temperature of the TEG and

α - the Seebeck coefficient of the TEG.

Parameters of TEG systems

- The current:

$$I = \frac{V}{R + RL}$$

- Electrical power:

$$P \; = \; Q_h - Q_c = I^2 \; \cdot RL$$

- Total amount of heat:

$$Q = \alpha \cdot I \cdot T_C + K \cdot (T_h - T_c) - {}^1/_2 \cdot I \cdot RL$$

where

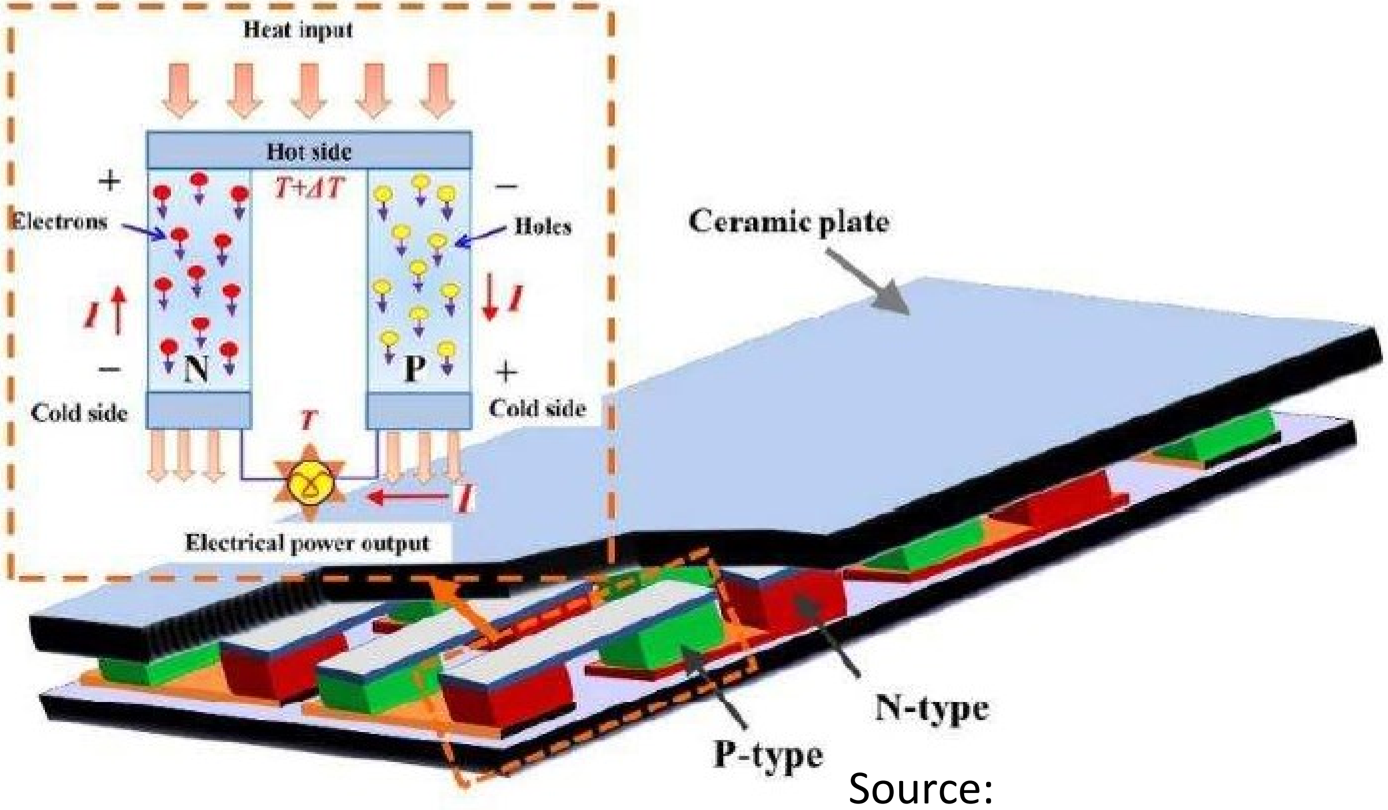
R -the internal resistance of TEG,

RL - the Load resistance,

(Qh – Qc) - the heat flux due to temperature gradient, and

K - the heat transfer coefficient.

Thermoelectric generators (TEG)



- The thermal electromotive force generated is function of the temperature gradient and number of N-type and P-type semiconductors
- The produced power can be controlled by arranging semiconductors and covering them with a thermally conductive, but electrically insulating ceramic plate.

Source:
Jiang, W, Yuan, D, Xu, S et al. (2017) Energy harvesting from asphalt pavement using thermoelectric technology. Applied Energy, 205. pp. 941-950.

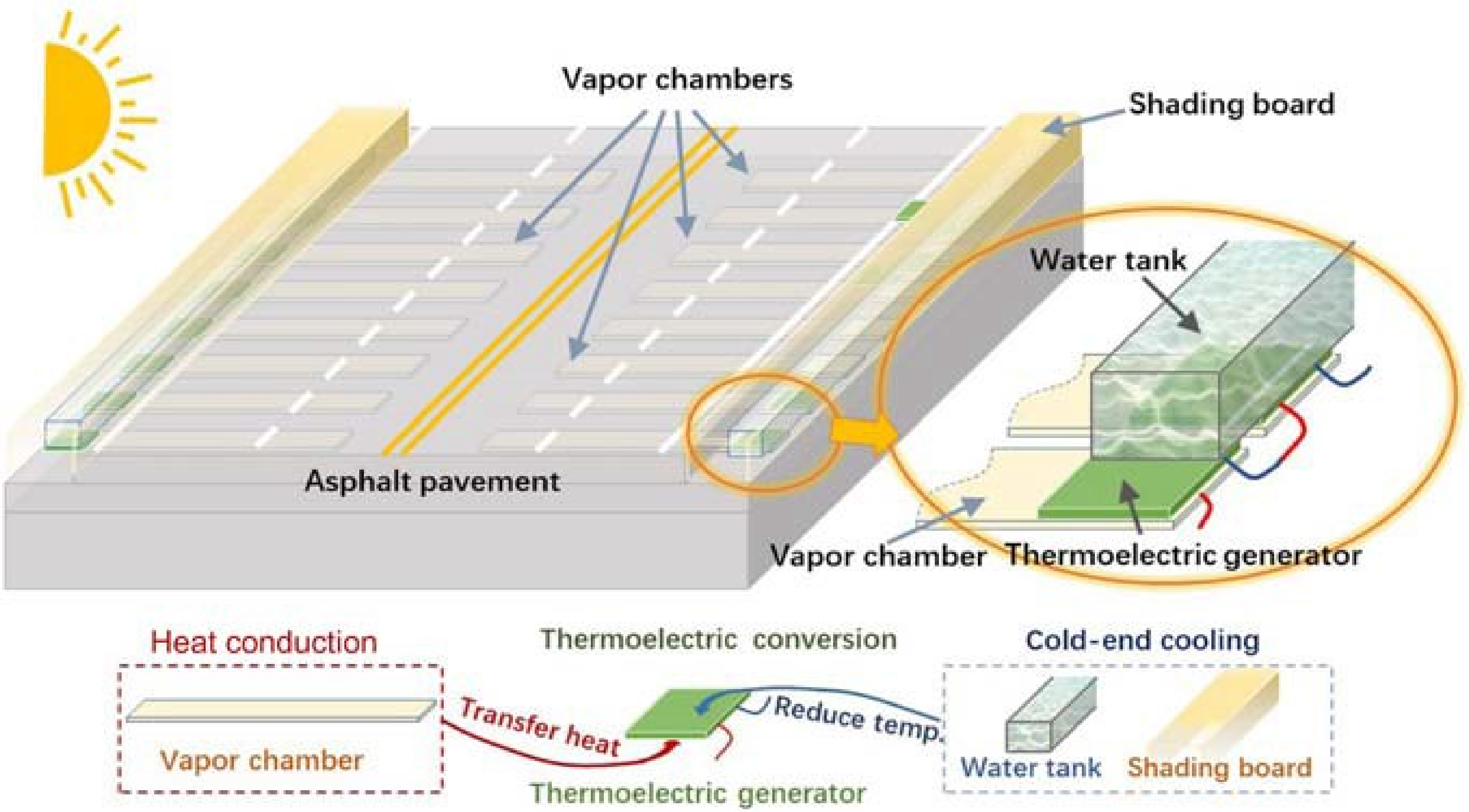
TEG Materials

- Should have low thermal conductivity and high electrical conductivity to perform effectively in converting the temperature gradient into electric energy
- Appropriate materials:
  - Silicon germanium (SiGe)
  - Bismuth Telluride (Bi2Te3)
  - Lead Telluride (PbTe)
- Thermal energy harvesters consists of:
  - TEG – several commercially available
  - Heat sink
  - Heat conducting plate – metal plate is convenient option. Absorbs heat from the pavement surface and transfers it to the point where the TEGs are installed.

Thermoelectric generators (TEG)

- Several types of TEG systems developed or under development:
  - Systems based on temperature difference between heated fluid in collection tubes within the pavement and the cool water from the outside source (e.g. river)
  - Systems based on use of temperature difference within the pavement structure

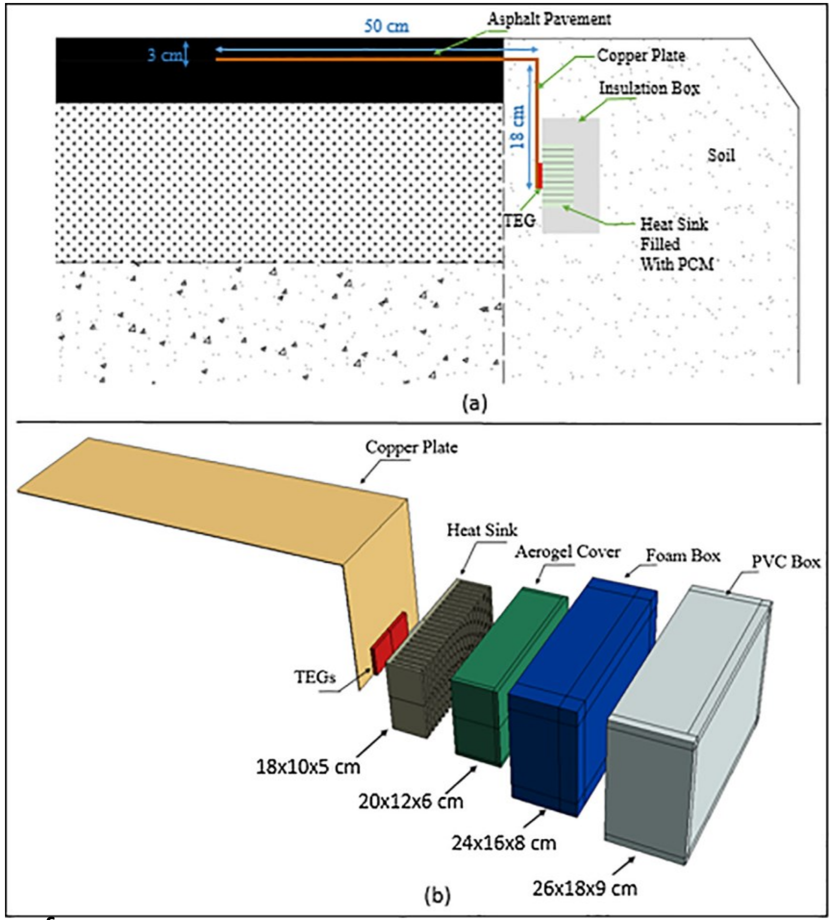
Road Thermoelectric Generator System (RTEGS)



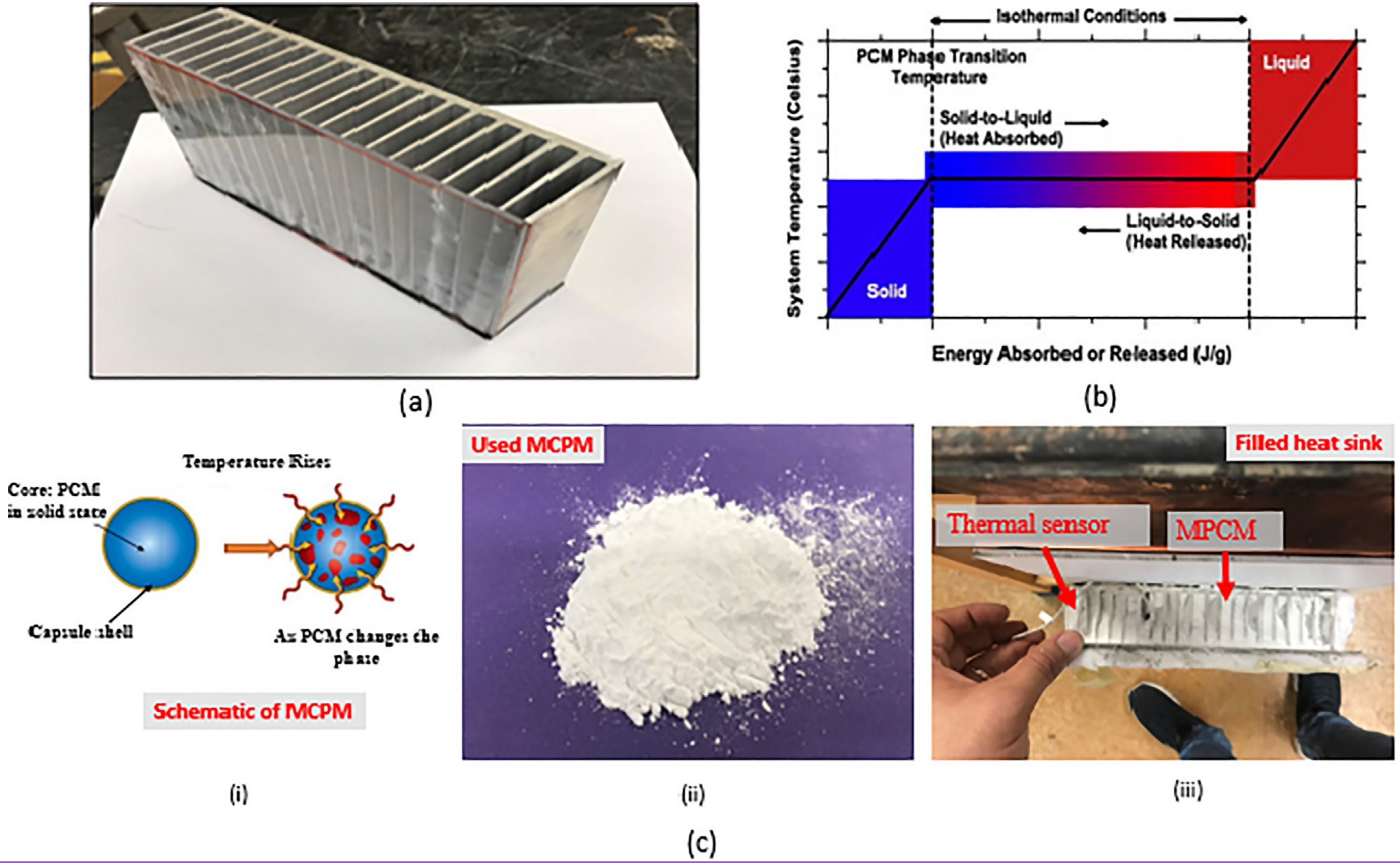
Jiang W. et al. (2018). “Design and experiment of thermoelectric asphalt pavements with power-generation and temperature-reduction Functions”, Energ Build;169:39–47.

Use of temperature difference within the pavement

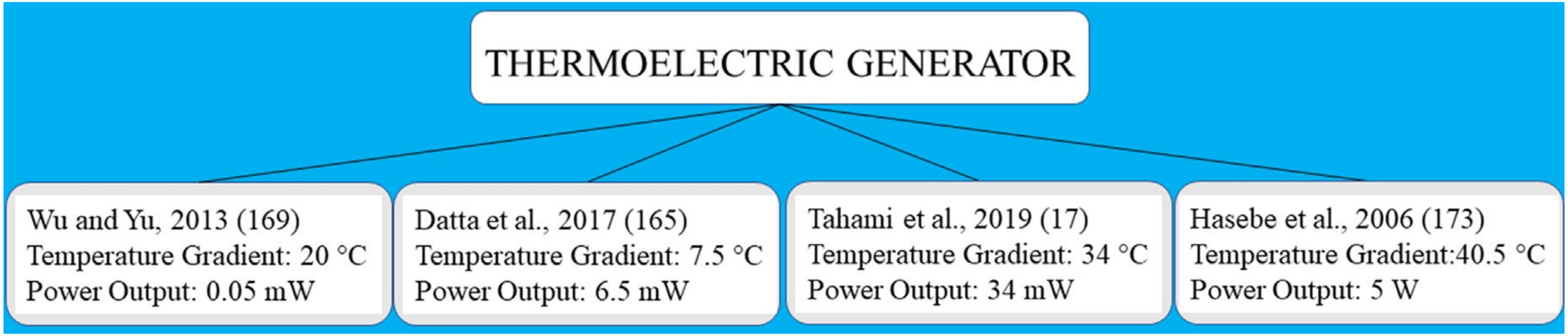
- One part of metal plate is typically located at surface, or near the surface (20-30 mm from the surface), while the other part is located deeper in the structure/subgrade
- Researchers at University of Texas, SA, have developed two prototypes, Z and L, using heat sink with phase change materials (PCM)



Source:
Tahami, S.A. et al. (2019). “Developing a new thermoelectric approach for energy harvesting from asphalt pavements, Applied Energy, 238, 786-795


Isothermal Conditions
PCM Phase Transition Temperature
Liquid
Solid-to-Liquid (Heat Absorbed)
Liquid-to-Solid (Heat Released)
Solid
System Temperature (Celsius)
Energy Absorbed or Released (J/g)
(a)
(b)
Temperature Rises
Core: PCM in solid state
Capsule shell
As PCM changes the phase
Schematic of MCPM
Used MCPM
Filled heat sink
Thermal sensor
MPCM
(i)
(ii)
(iii)
(c)

Efficiency of TEG Systems



- Estimated levelized cost of energy (LCOE) ranges between 0.3 – 2.3 $/kWh

Source:
Gholikhani M. et al. A critical review of roadway energy harvesting technologies, Applied Energy, 261 (2020)

Advantages and difficulties of TEG systems

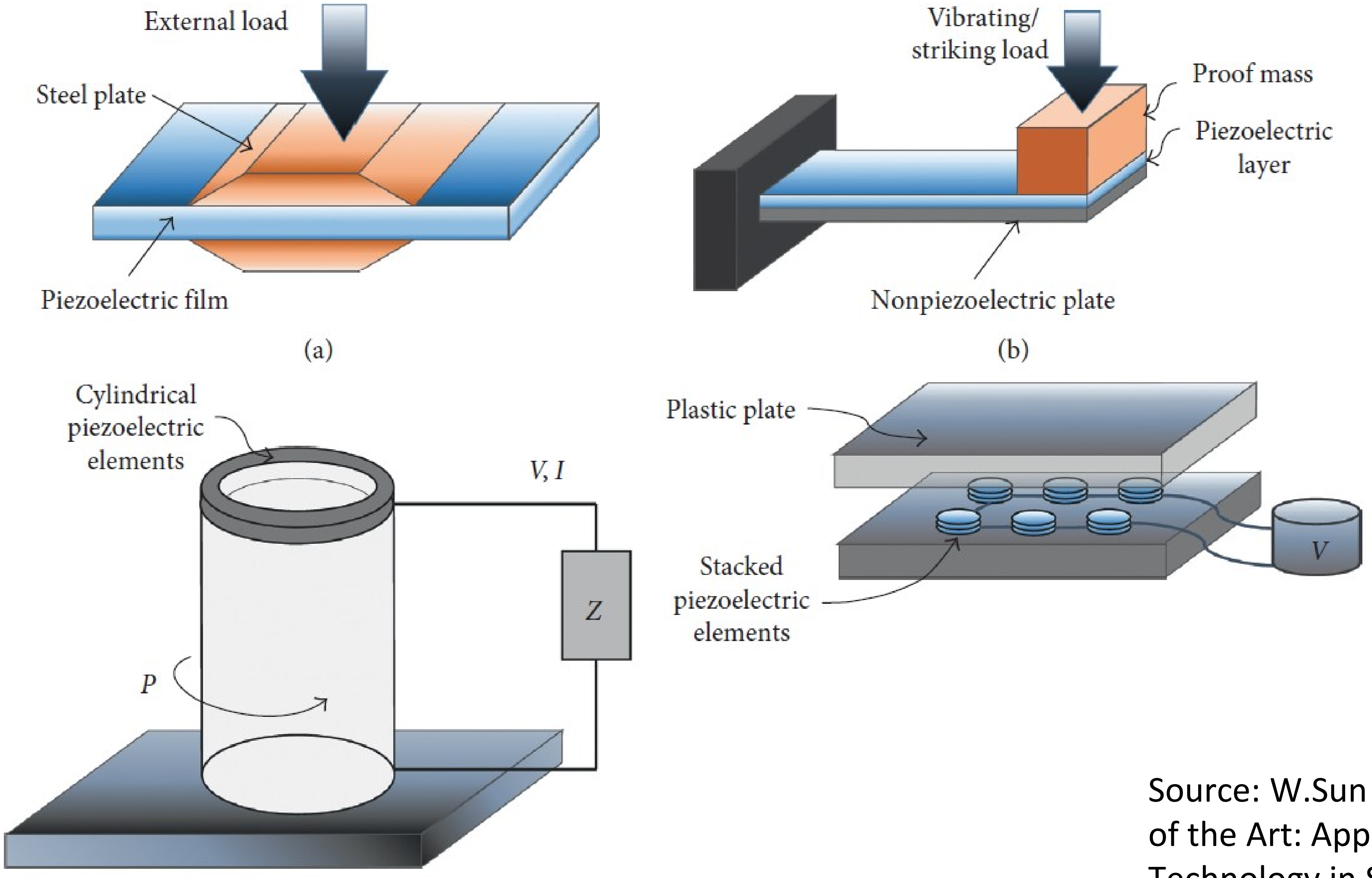
- Advantages
  - No moving mechanical parts
  - Relatively simple maintenance
- Difficulties
  - Relatively small temperature gradient within the pavement structure (should be increased if possible)
  - How to effectively use the temperature difference within the pavement structure, which is usually relatively small, and
  - How to maintain the thermoelectric conversion efficiency of the pavement under different environmental conditions?

Harvesting of mechanical energy

- Several possible technologies:
  - Based on piezoelectric effects
  - Hydraulic/Pneumatic
  - Electromagnetic
  - Electrostatic
  - Pyroelectric
  - …

Piezoelectric harvesting systems (PEH)

- The piezoelectric phenomenon was discovered by Pierre and Jacques Curie, in 1880.
- The piezoelectric material can produce electricity when subjected to mechanical stress capable of deforming its geometry.
- Different materials can have piezoelectric properties:
  - single crystalline material,
  - piezoceramics,
  - piezoelectric semiconductors,
  - polymer,
  - piezoelectric composites, and
  - glass ceramics.



(c) (d)

Source: W.Sun et al. (2018). The State of the Art: Application of Green Technology in Sustainable Pavement, Advances in Materials Science and Civil Engineering, Vol. 2018

Output and efficiency of PEH systems

- PEH systems generate relatively low energy
- Need to be stored either is supercapacitors or rechargeable batteries
- LCOE for different prototypes ranges between 2 and more than 100 $/kWh
- Few commercialized systems:
  - Innowatech
  - Genziko
  - …

Source: https://www.pavegen.com/en/case-studies?hsLang=en

Difficulties of PEH Systems

- The two main problems related to the use of piezoelectric materials are:
  - the poor resistance and durability under traffic load, and
  - the mismatch between stiffness of piezoelectric materials and pavement materials.

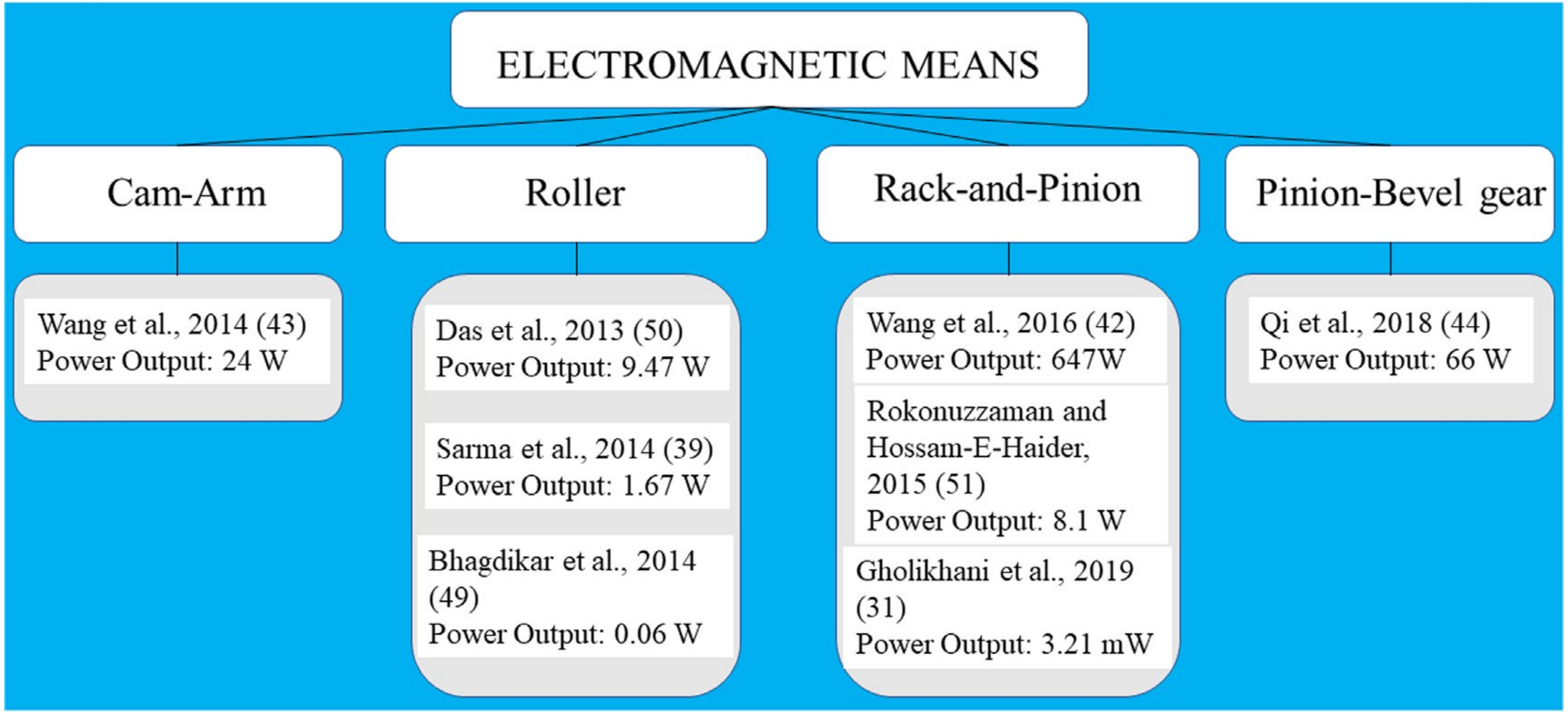
Electromagnetic (EM) generators

- EM devices absorb the mechanical energy from passing vehicles and convert it to a movement that actuates an electrical motor that functions on Faraday's principle.
- Faraday's principle: the relative movement of an electric conductor with respect to a magnetic field induces an electric current.
- The amount of electricity generated depends on the:
  - velocity of relative movement,
  - the strength of the magnetic field, and
  - the number of coils.

EM Generators

- Actuated through interface that can be:
  - Hydraulic/Pneumatic
  - Electromechanical
  - Micro-electromechanical (MEMS)
- Significant amount of ongoing research resulting in many patents using laboratory and field installed prototypes

Output of potential EM systems



Potential applications of EM systems

Source:
Duarte, F. & Ferreira, A. (2021). “Energy harvesting on road pavements: state of the art”. Proceedings of the Institution of Civil Engineers, Energy 169 May 2016 Issue EN2

Pyroelectric systems

- Some piezoelectric materials have pyroelectric ability to convert thermal energy to electrical energy when heated or cooled.
- The pyroelectric current is directly proportional to the rate of change in temperature.

Advantages and disadvantages of various technologies

Technology	Advantage	Disadvantages
Photovoltaic	High energy output	High cost, susceptible to traffic loading, low skid resistance, weather dependent (depends on direct solar radiation and shadow situation), vulnerable to dust and dirt
ASC with liquid	High energy savings	Negative effect on pavement construction and maintenance, weather dependent, needs energy for operation, leakage problems
ASC with air	NA	Weather dependent, very low efficiency, does not work in cold weather
Thermoelectric	Wide applicability Easily applied with other technologies	Low efficiency and high cost per unit, weather dependent
Piezoelectric	In all roadways, independent from weather condition, variety of designs, no adverse effects on pavement life	High cost for high energy output Needs support to resist to traffic loads
Pyroelectric	Adds output energy to piezoelectric material output	Fully dependent on piezoelectric technology, low efficiency
Electromagnetic	High electrical power output, independent from weather conditions, variety of designs,	High maintenance cost due to mechanical parts Not applicable to all roads

Comparison of different technologies

Technology	Peak power output	Power density	Levelized cost of energy ($/kWh)	Technology Readiness Level	Efficiency
Photovoltaic	220 W	48 W/m^2	0.45	3	Medium to high
ASC with liquid	NA	NA	4.21	3	Medium to high
ASC with air	NA	NA	NA	NA	Low
Thermoelectric	42 mW	41 $\mu W/cm^2$	0.89	3	Medium to high
Pyroelectric	0.33 µW	0.33 $\mu W/cm^2$		3	Low
Piezoelectric	1.8 W	647 mW/cm^2	27.90	4	Medium
Electromagnetic	647 W	647 W/m^2	NA	2	Medium to high

Adapted from:
Gholikhani M. et al. A critical review of roadway energy harvesting technologies, Applied Energy, 261 (2020)

Conclusions

- Solar radiation presents the main source of renewable energy that can potentially be harvested by pavements. However, systems that use vehicle mechanical energy have high potential in terms of efficiency and adaptability to road pavements.
- Asphalt solar collectors have been already implemented in many countries, with primary purpose for providing energy for de-icing existing pavements.
- There are many other technologies under development and at different technology readiness levels, with the objective to produce electrical energy.
- Thermoelectric and Piezoelectric technologies are the most readily available methods. Most of current research is related to use of electromagnetic generators.

Barriers to wider energy harvesting

- Consumers of the energy may not be close to the pavement giving energy conveyance problems, particularly in rural areas.
- Constructing harvesting arrangements that don't negatively impact the pavement from delivering its primary function, carrying traffic, is not a trivial issue.
- Maintenance of the harvesting arrangements and of the pavement must be achievable without disrupting the other.
- Conventional pavement construction sequences, materials and plant may not be best suited to installing energy harvesting equipment.

Barriers to wider energy harvesting

- In the developed world most pavements are already constructed so harvesting systems would usually need to be retro-fitted and this will probably be difficult/expensive/disruptive.
- Initially, the durability of pavements equipped with energy harvesting arrangements won't be understood very well, causing planning difficulties for pavement managers.
- As with all solar systems, the energy abstractable is weather and time-of day dependent so consumers will almost certainly require an alternative source as well, decreasing economic efficiency.

THANK YOU!

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