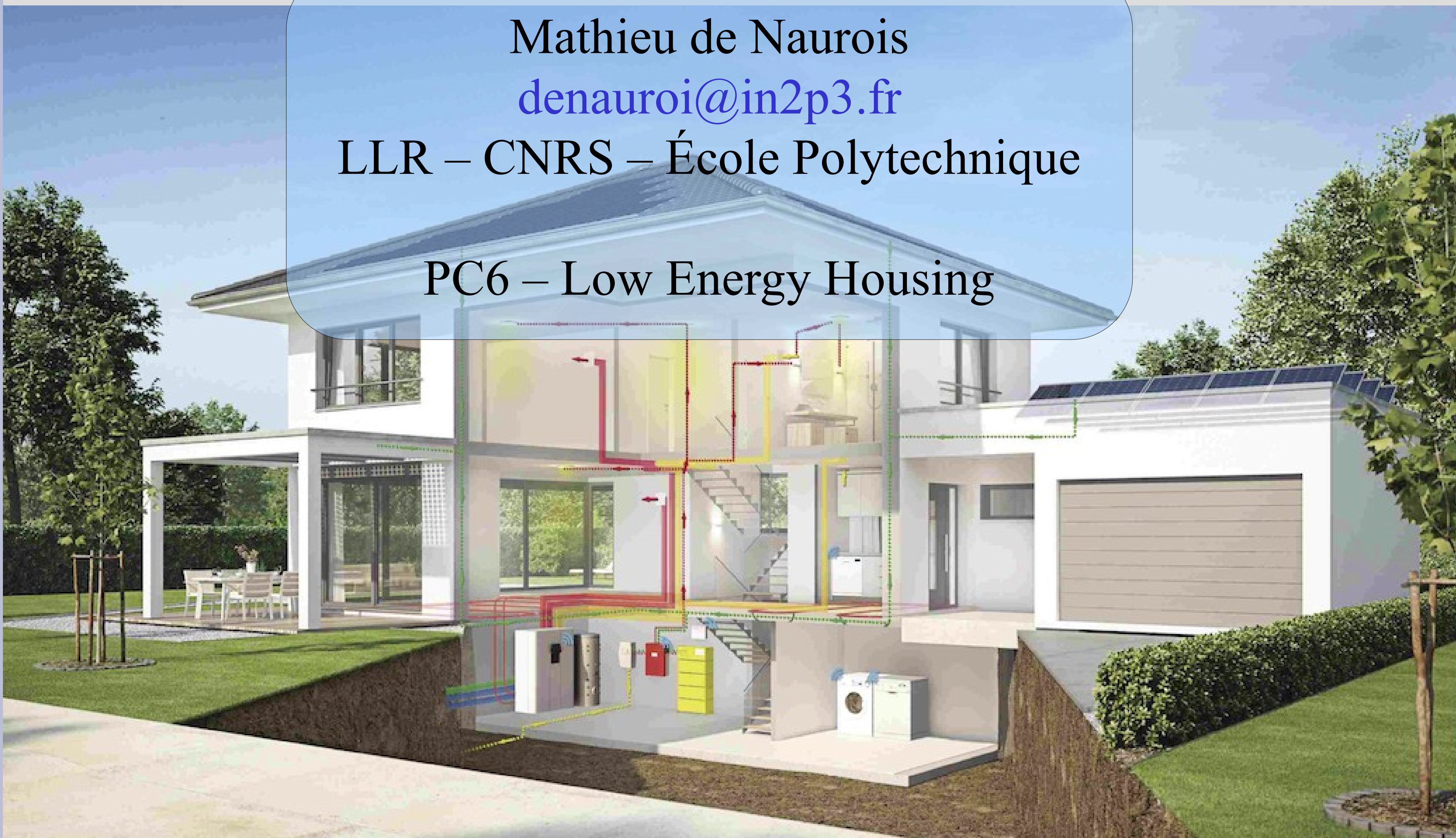
Energy and Environnement



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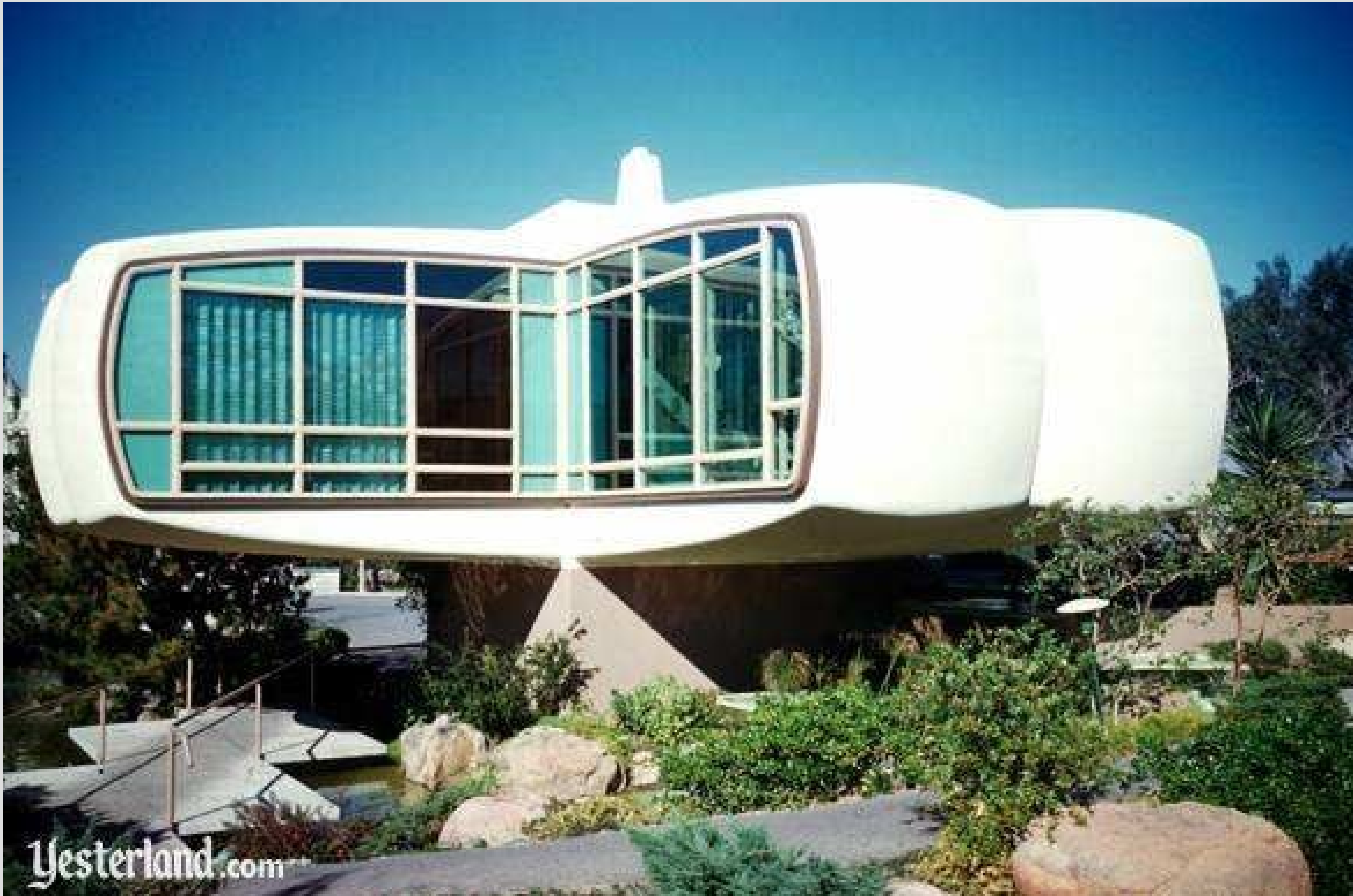
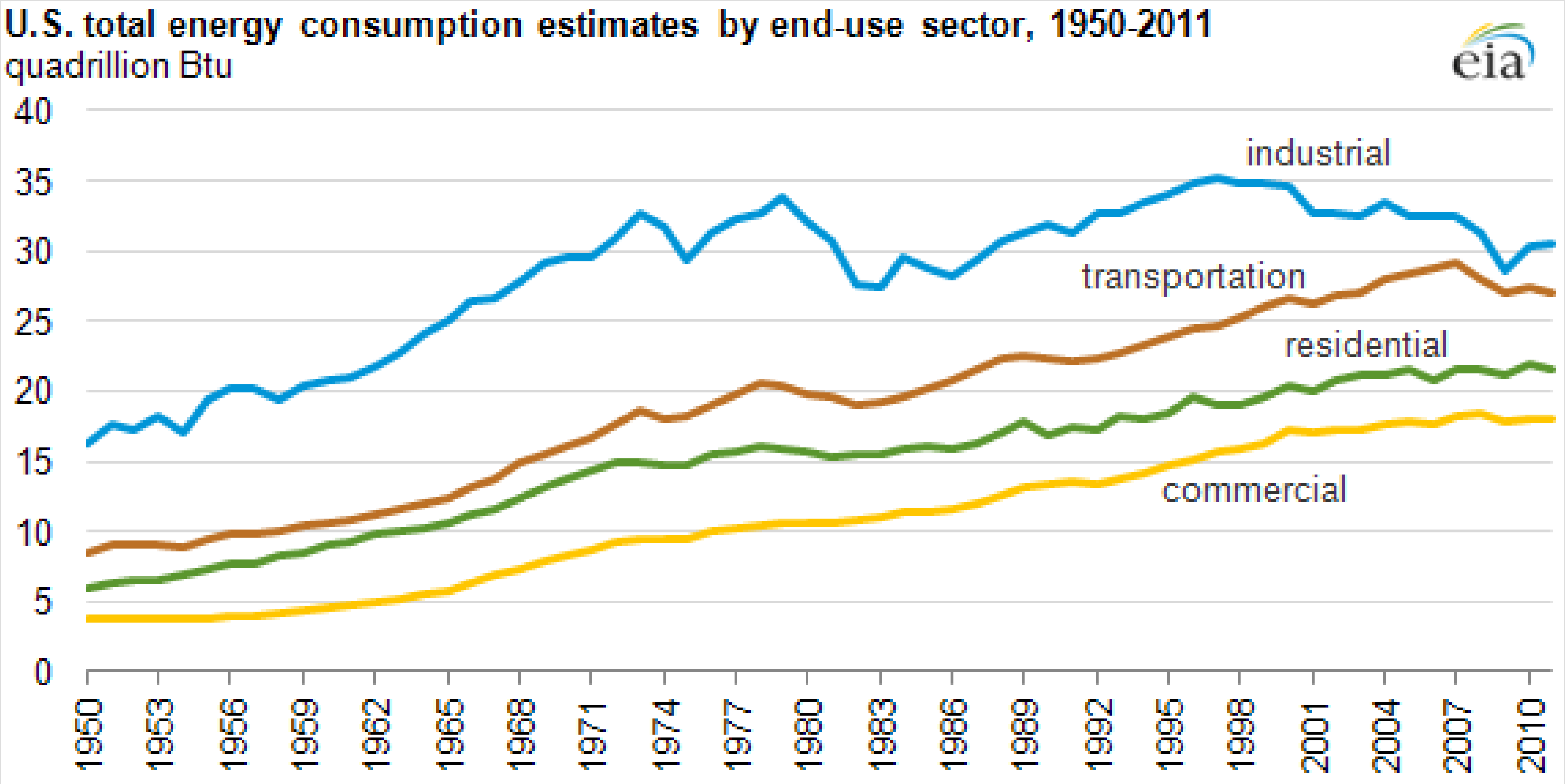
PC6 – Low Energy Housing

The individual house of the future – in 1960

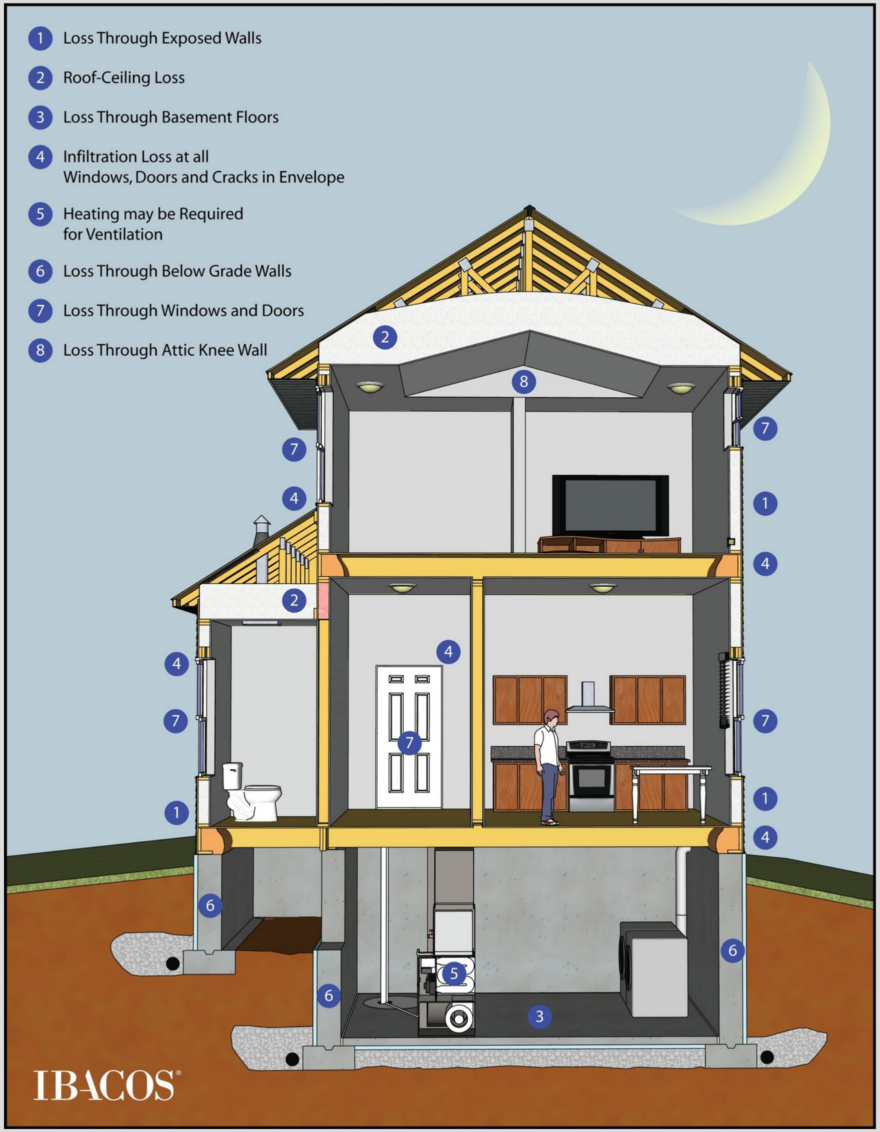


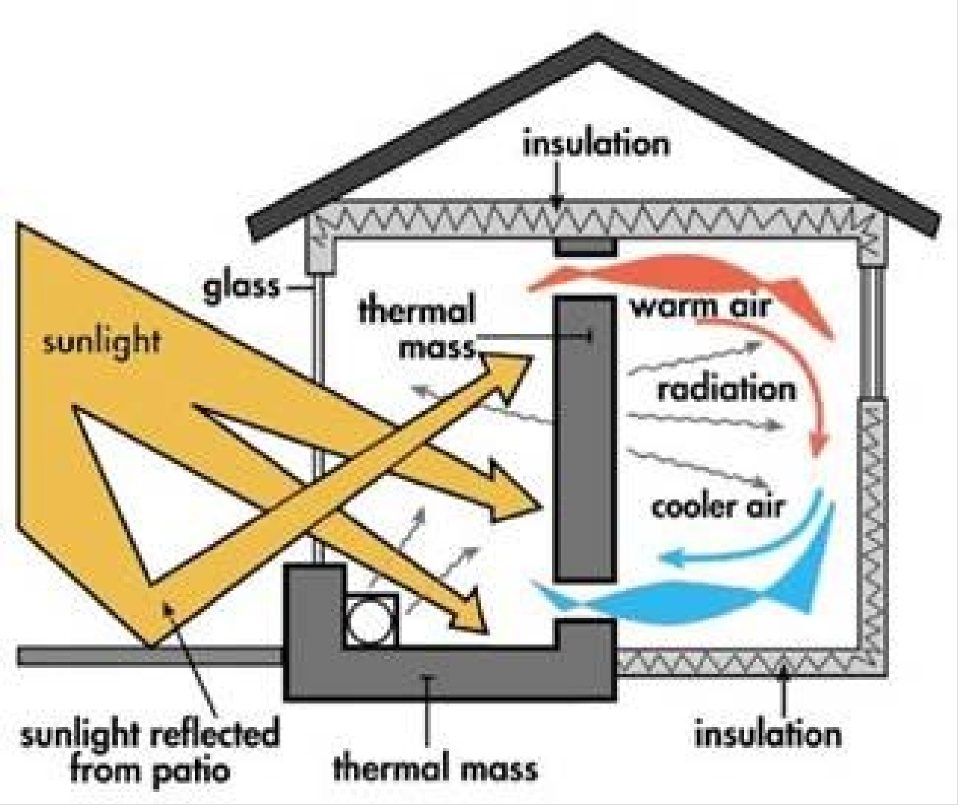
The individual house of the future – in 2020 ?

Energy consumption per sector



Heat Balance





Domestic Consumption in France

Consumptions in kWh/m^2.yr (10 kWh # 1 litre of fuel oil)

	1970	**1988**	**Passive House**
Envelope	130	50	10
Ventilation	50	30	15
Hot water	30	30	20
Specific Electricity (home appliance, lighting,...)	80	50	25
Total	**290**	**160**	**70**

Source Cythélia

Envelope Insulation

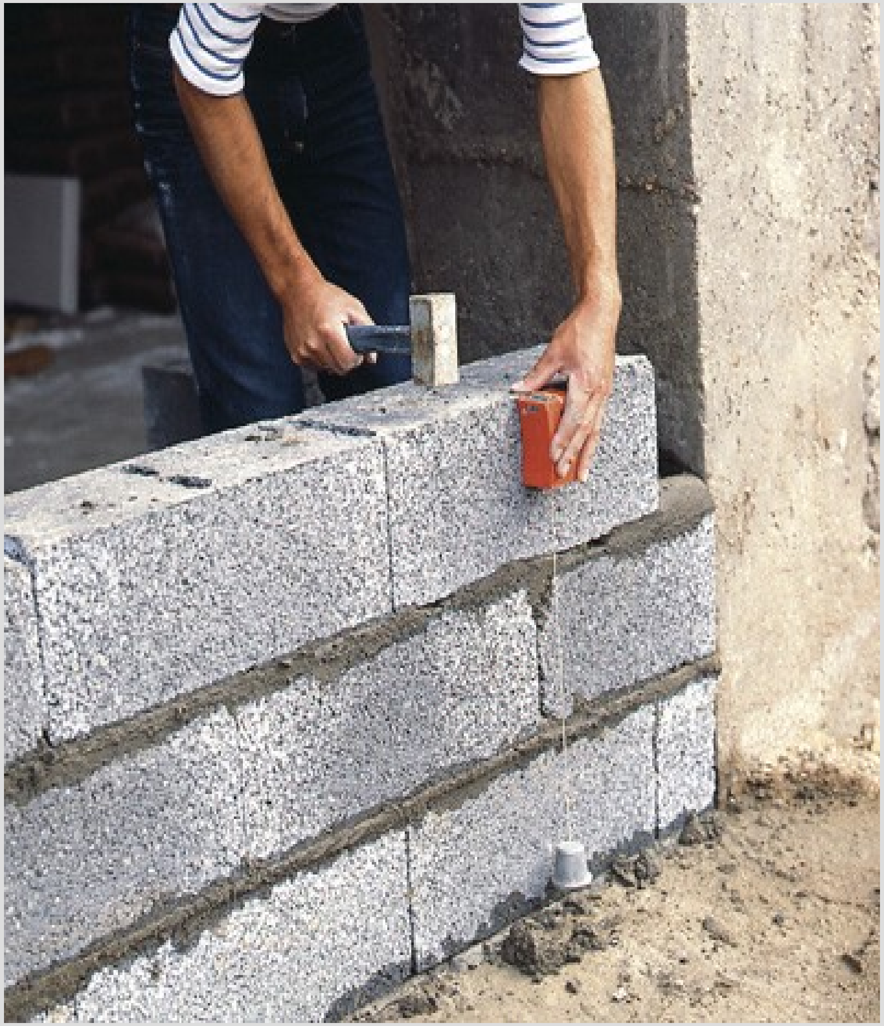
Calculation of leakage

- non-insulated house
- traditional insulation (polystyrene)
- wood frame house
- windows (20%)

	Rth	Leakage			fuel cost	grey Energy	
	$kW^{-1}m^2$	$W\ m^{-2}$	$kWh\ m^{-2}\ a^{-1}$	$MWh\ a^{-1}$	€/a	$kWh\ m^{-2}$	MWh
without insulation							
traditional insulation							
windows (20%, single glazing)							
wood frame house							

Hollow cellular concrete blocks

Material	λ (W/K/m)	G. energy (kWh/m³)
Ordinary concrete	2,1	900
Cellular concrete	0,2	300
Hollow cellular concrete blocks 20 × 20 × 50 mm	1,15	410
Full brick	0,8	1 200
Hollow brick	0,4	675
Plasterboard BA13	0,25	1 450
Softwood	0,13	150
Wood particles panel	0,16	150
Insulating brick	0,11	
Straw	0,055	
Conventional insulation (polystyrene)	0,04	450
High performance insulation (polyurethane foam)	0,04	1 000
Cellulose wool	0,04	6 to 10
Glass	1	11 400
Immobile dray air	0,04	



Thermal calculations

- FOURIER's law

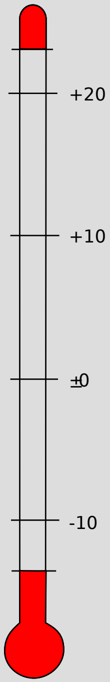
  $$\vec{j}_Q = -\lambda \vec{\nabla} T \quad \left[\mathrm{W\, m^{-1} K^{-1}} \right]$$

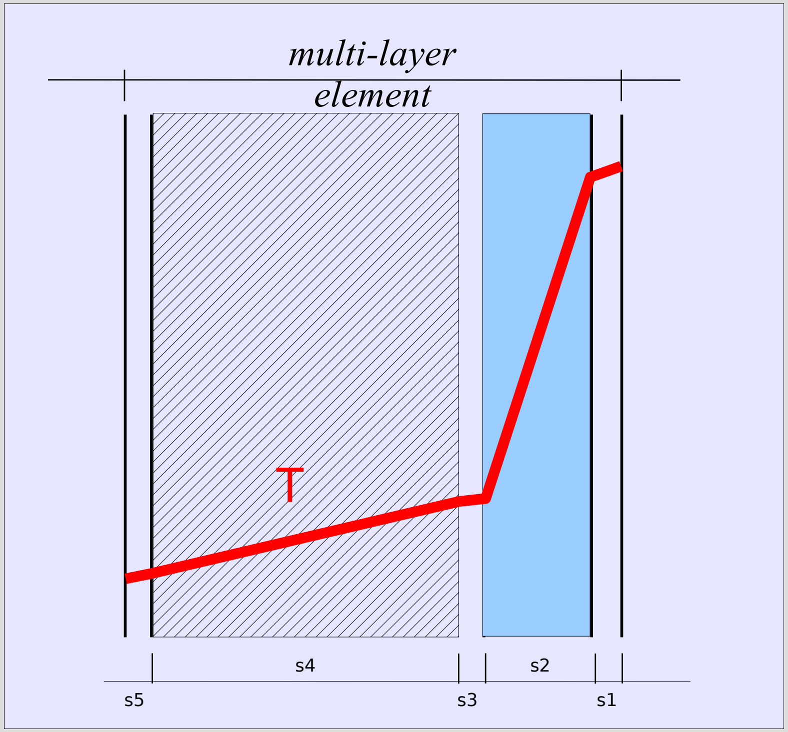
- Thermal conductivity: λ
- semi-empirical law!
- more general: Newton's law

  $$\Delta \dot{Q} = h A \Delta T$$

- Heat transfer coefficient h
- If thermal conduction, transfer coefficient is proportional to inverse thickness

  $$h = \lambda / d$$





Calculation of leakage

- classical, non-insulated house, walls: 130 m², living space 100 m²
- fuel oil heating (PCI×η ≈ 9kWh/l), cost 1,4 €/l (2022)
  → 155 €/MWh
- Electricity current price: 190 €/MWh

	Rth	Leakage			fuel cost	grey Energy	
	$kW^{-1}m^2$	$W\ m^{-2}$	$kWh\ m^{-2}\ a^{-1}$	$MWh\ a^{-1}$	€/a	$kWh\ m^{-2}$	MWh
without insulation	**0,174**	**57,5**	**503,4**	**65,4**	**10 137**		
traditional insulation							
windows (20%, single glazing)							
wood frame house							

Thermal calculations

- FOURIER's law

$$\vec{j}_Q = -\lambda \vec{\nabla} T \quad [\mathrm{W\,m^{-1}\,K^{-1}}]$$

- Newton's law

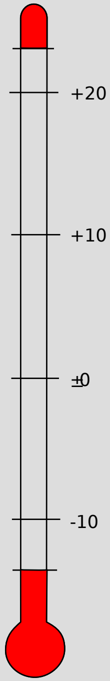
$$\Delta \dot{Q} = h\, A\, \Delta T$$

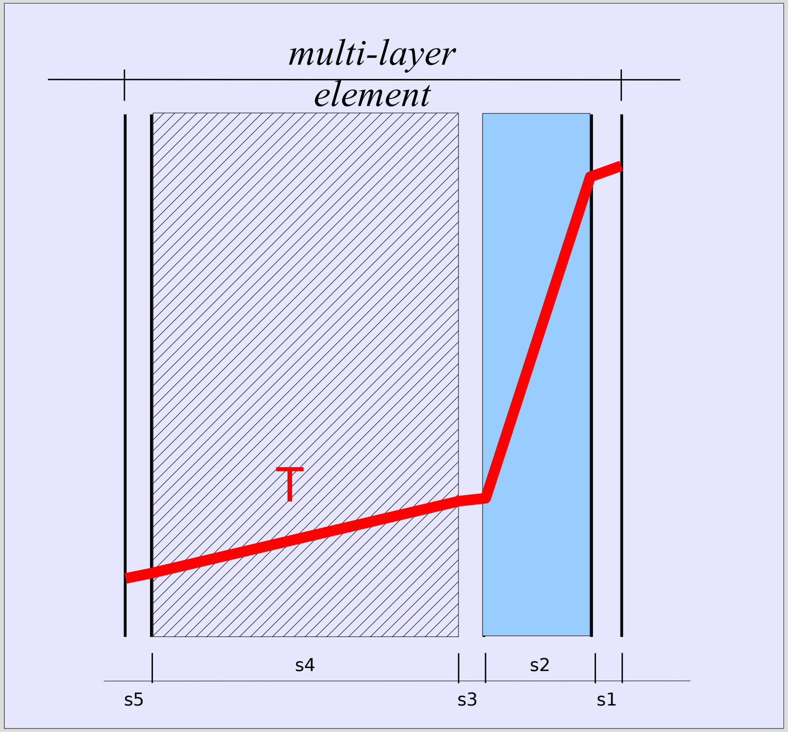
- Thermal linear resistance:

$$R_l = \frac{1}{\lambda} \quad [\mathrm{m\,K\,W^{-1}}]$$

- Multilayer element

$$R_e = \sum_i \frac{s_i}{\lambda_i} \quad [\mathrm{m^2\,K\,W^{-1}}]$$





$$j_Q = \lambda \frac{\Delta T}{s} = \frac{\Delta T}{R_e}$$

Traditional Insulation

Material	λ (W/K/m)	G. energy (kWh/m³)
Ordinary concrete	2,1	900
Cellular concrete	0,2	300
Hollow cellular concrete blocks 20 × 20 × 50 mm	1,15	410
Full brick	0,8	1 200
Hollow brick	0,4	675
Plasterboard BA13	0,25	1 450
Softwood	0,13	150
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Insulating brick	0,11	
Straw	0,055	
Conventional insulation (polystyrene)	0,04	450
High performance insulation (polyurethane foam)	0,04	1 000
Cellulose wool	0,04	6 to 10
Glass	1	11 400
Immobile dray air	0,04	

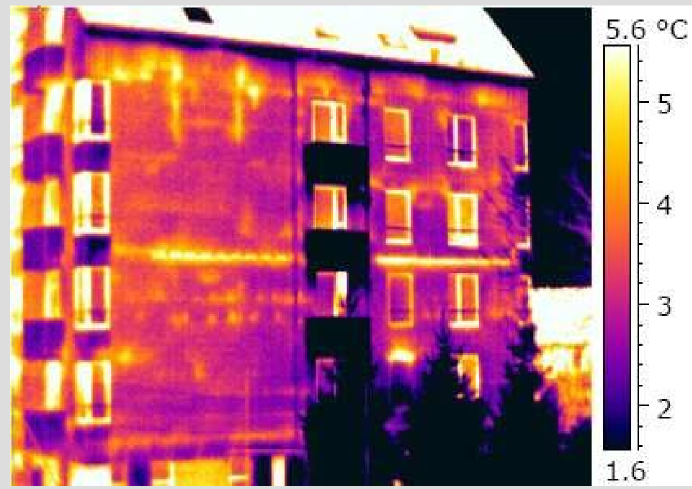
Calculation of leakage

- classical house with traditional insulation (polystyrene)

	Rth	Leakage			fuel cost	grey Energy	
	$K.W^{-1}m^2$	$W\ m^{-2}$	$kWh\ m^{-2}\ a^{-1}$	$MWh\ a^{-1}$	€/a	$kWh\ m^{-2}$	MWh
without insulation	0,174	57,5	503,4	65,4	10 137	82	10,7
traditional insulation	1,226	8,2	71,5	9,3	1 440	37	4,8
windows (20%, single glazing)							
wood frame house							

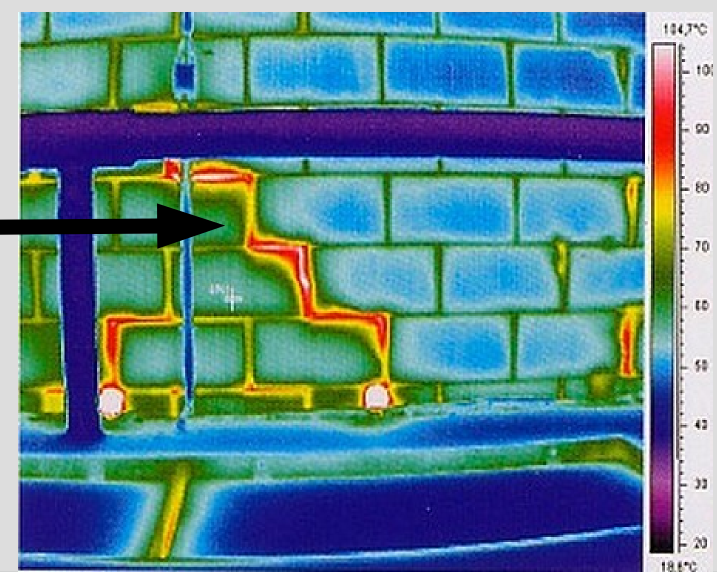
Thermal measurements

- Use of infrared camera for the detection of thermal bridges
  - Measurements to be done during cold nights (cold outside air)

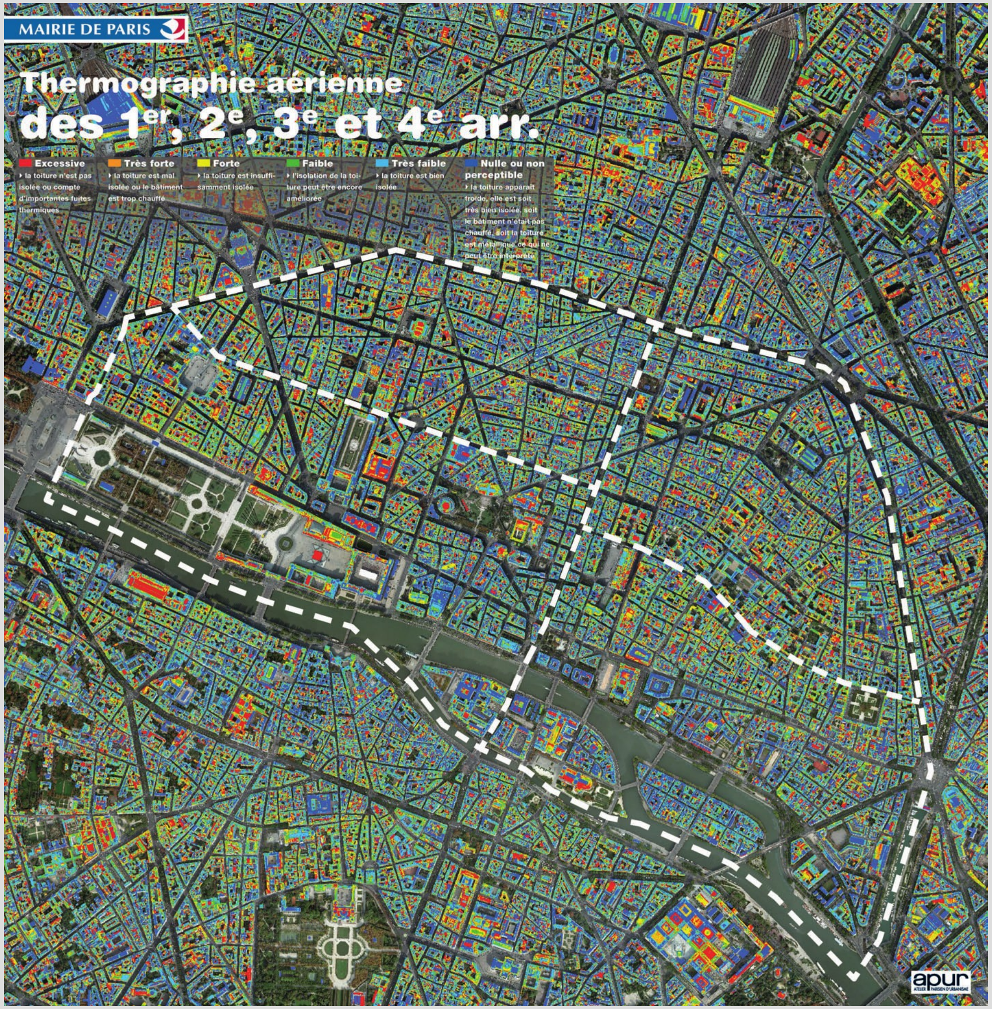


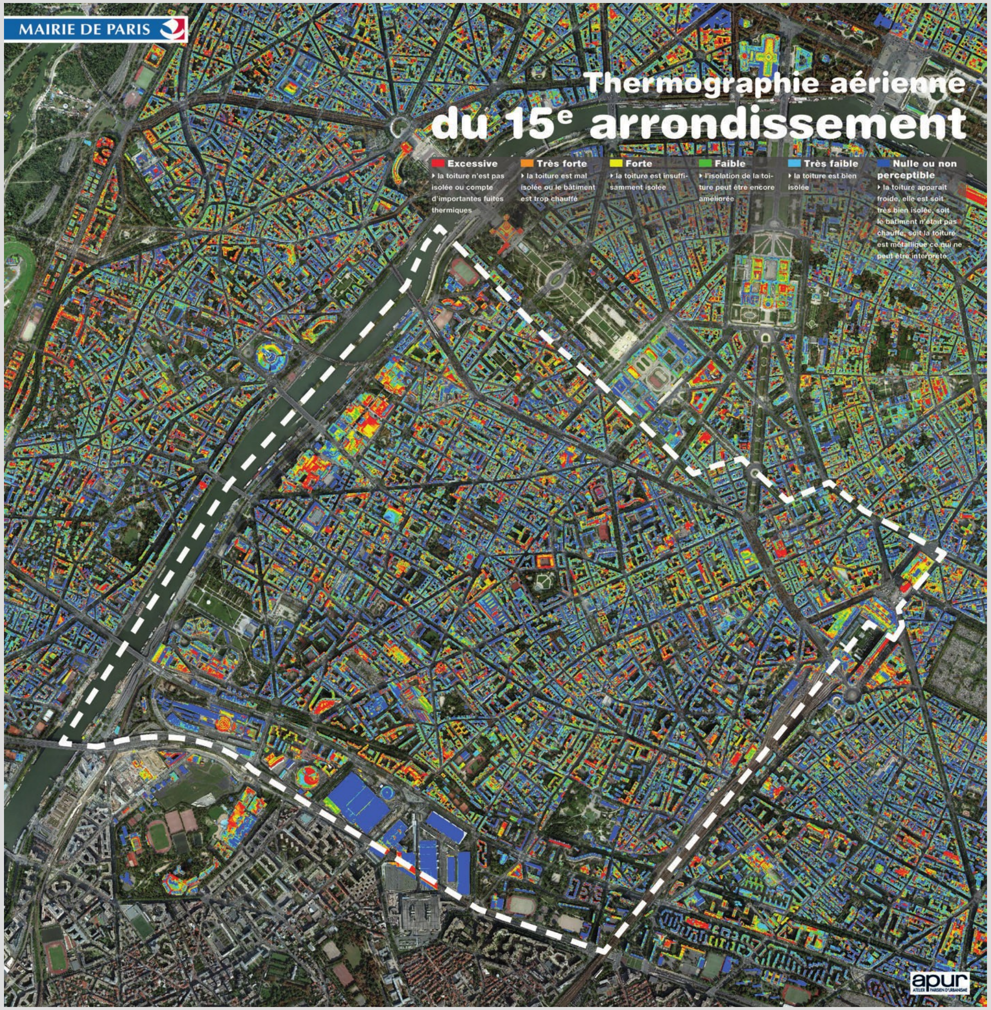
Thermal bridge at floor level

Crack in a wall

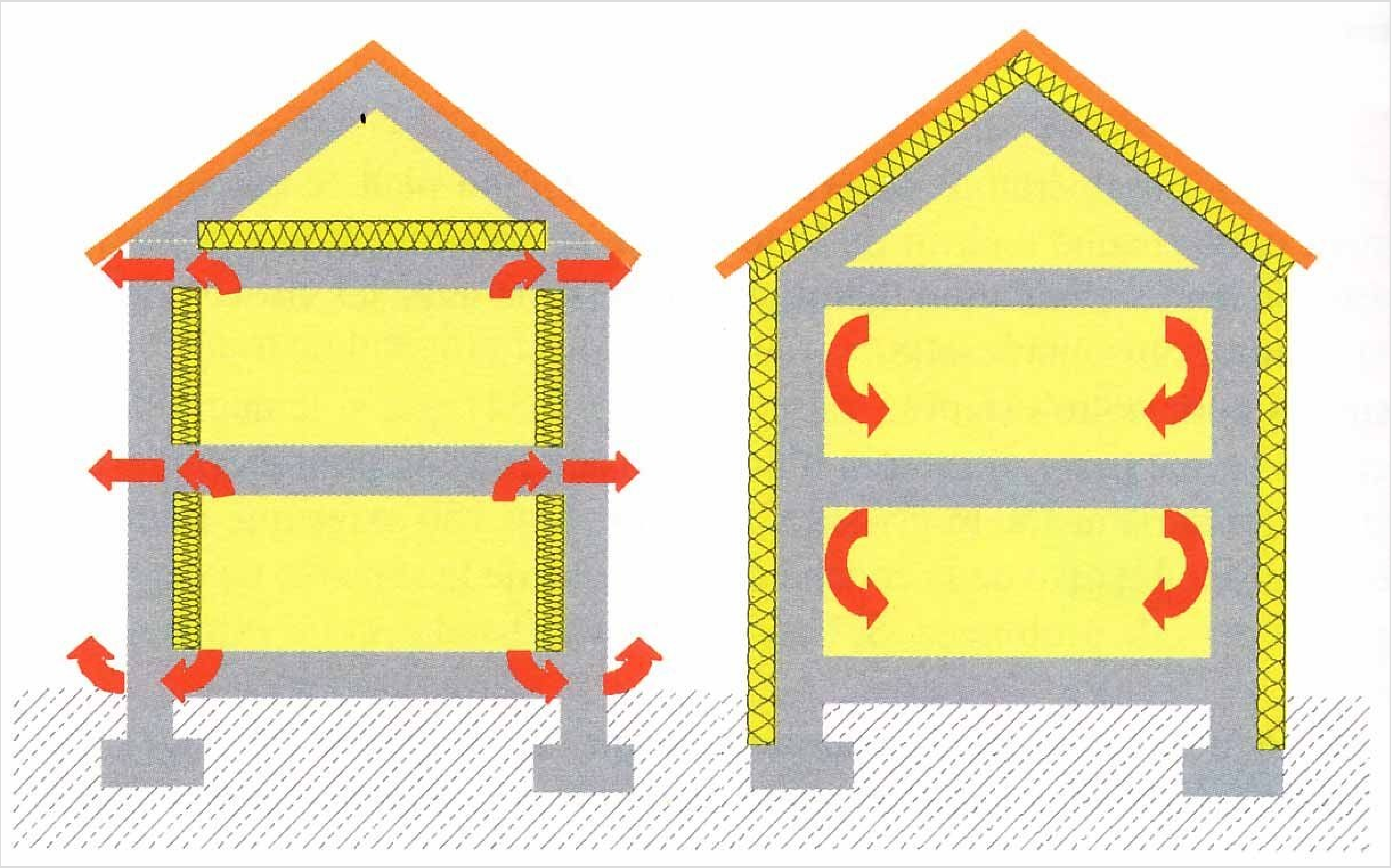


Aerial Thermography of Paris

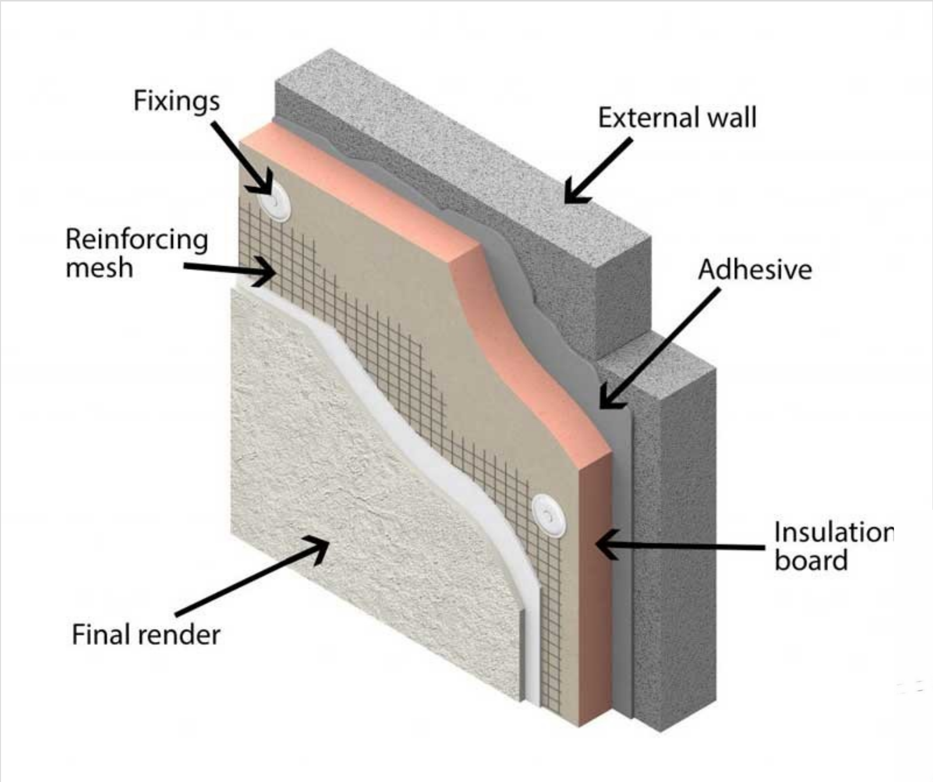




To avoid thermal bridges: prefer outside insulation



External Insulation & Finishing System (EIFS)



- Insulated, water-resistant, finished surfaced in an integrated composite material system

Glass

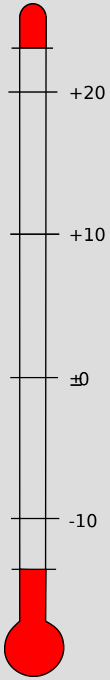
Material	λ (W/K/m)	G. energy (kWh/m³)
Ordinary concrete	2,1	900
Cellular concrete	0,2	300
Hollow cellular concrete blocks 20 × 20 × 50 mm	1,15	410
Full brick	0,8	1 200
Hollow brick	0,4	675
Plasterboard BA13	0,25	1 450
Softwood	0,13	150
Wood particles panel	0,16	150
Insulating brick	0,11	
Straw	0,055	
Conventional insulation (polystyrene)	0,04	450
High performance insulation (polyurethane foam)	0,04	1 000
Cellulose wool	0,04	6 to 10
Glass	1	11 400
Immobile dray air	0,04	

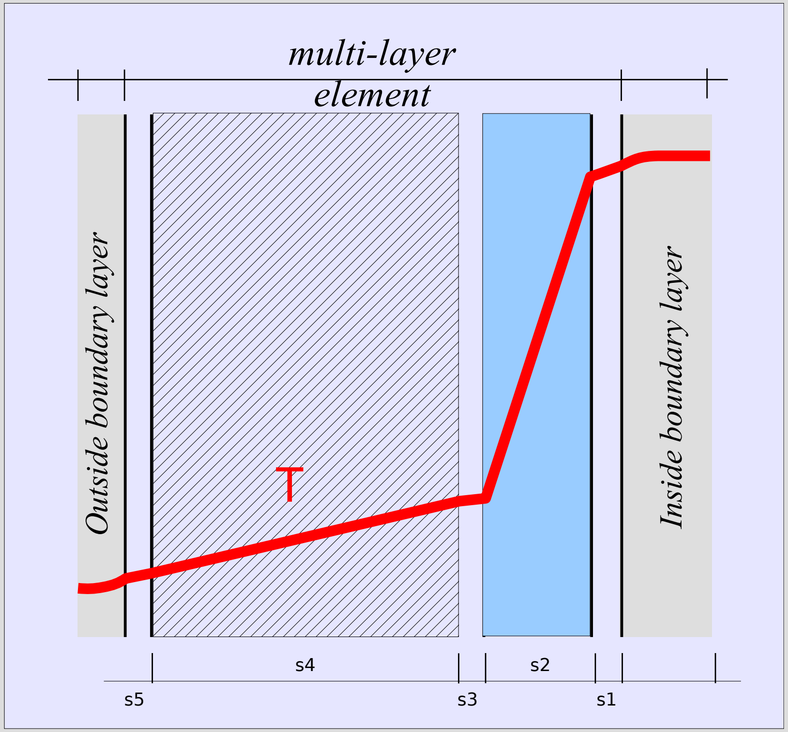
- single glazing (5 mm) :
  $h = 5{,}7\ Wm^{-2}K^{-1}$
- double glazing (4+12+4mm) :
  $h = 2{,}9\ Wm^{-2}K^{-1}$
- high performance double glazing:
  $h = 0{,}5\ Wm^{-2}K^{-1}$

source: Saint-Gobain Glass

Boundary layer

- Complex problem of fluid mechanics
- Depends on wind speed, viscosity, surface roughness, object shape, flow regime (laminar/turbulent)
- Mixture of convection/conduction
- Of the order of ~ 1cm for a windows





$$J_Q = \Delta T / R_e$$

Heat transfer coefficient

- Depends on the orientation of the surface and the nature of convection (natural, forced)
- Determined in a semi-empirical way

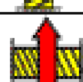
$R_s = 1/(h_r + h_a)$

h_r radiative exchanges $= 4\epsilon\sigma T^3 \approx 5$

h_a convecto-conduction exchanges

Heat Flow	ha
Ascending	5,0
Horizontal	2,5
Descending	0,7
Outside	4 + 4 v

v: wind speed en ms^{-1}

Surface	Flow	Rsi	Rse **	Rsi+Rse
Vertical		0,13	0,04	0,17
Horizontal		0,10	0,04	0,14
		0,17	0,04	0,21

** for v_{vent} = 4 m/s = 14 km/h

source: http://herve.silve.pagesperso-orange.fr/deperditions/deperd_rt2000.htm

Thermal Calculations

- Linear Thermal Resistance:

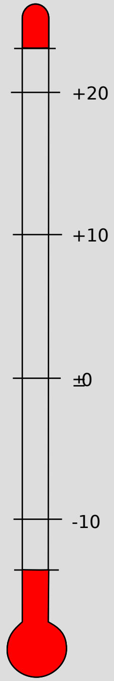
$$R_l = \frac{1}{\lambda} \quad \left[\mathrm{m\,K\,W^{-1}}\right]$$

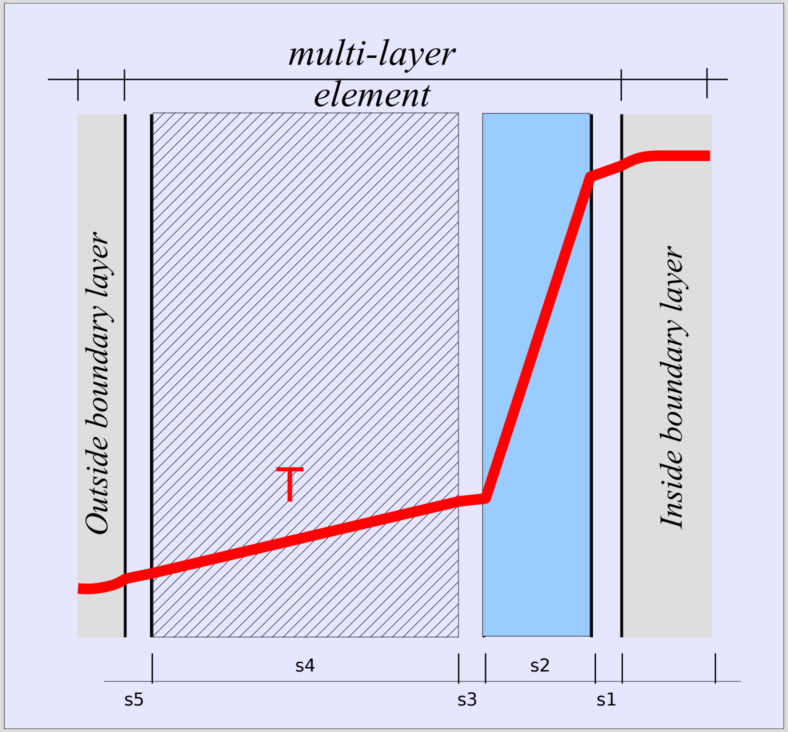
- Multilayer structure

$$R_e = \sum_i \frac{s_i}{\lambda_i} \quad \left[\mathrm{m^2\,K\,W^{-1}}\right]$$

- Boundary
  - Radiation + convection
  - outside: heat transfer depends on wind speed
  - Average equivalent resistance :

$$R_e \approx 0{,}17\,\mathrm{m^2\,K\,W^{-1}}$$





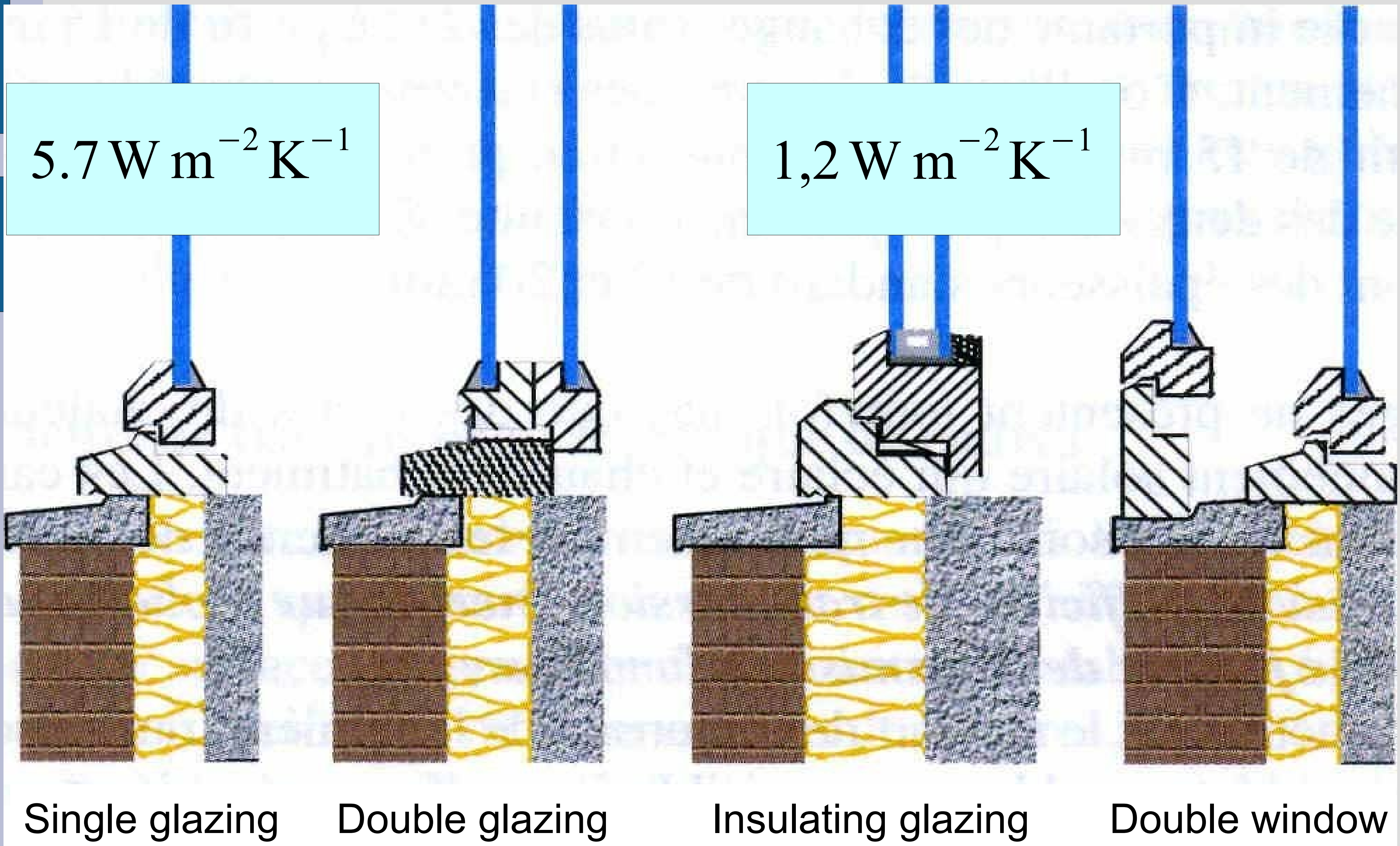
$$J_Q = \Delta T / R_e$$

Calculation of leakage

- windows: 20% of wall area (130 m^2)

	Rth	Leakage			fuel cost	grey Energy	
	$K.W^{-1}m^2$	$W\ m^{-2}$	$kWh\ m^{-2}\ a^{-1}$	$MWh\ a^{-1}$	€/a	$kWh\ m^{-2}$	MWh
without insulation	0,174	57,5	503,4	65,4	10 137	82	10,7
traditional insulation	1,226	8,2	71,5	9,3	1 440	37	4,8
windows (20%, single glazing)	**0,170**	**58,8**	**515,3**	**13,4**	**2 077**		
windows (20%, improved glazing)							
wood frame house							

Glazing



High performance glazing: $0{,}57\,W\,m^{-2}\,K^{-1}$

Calculation of leakage

- windows: 20% of wall area (130 m^2)

	Rth	Leakage			fuel cost	grey Energy	
	K.W^{-1}m^2	W m^{-2}	kWh m^{-2} a^{-1}	MWh a^{-1}	€/a	kWh m^{-2}	MWh
without insulation	0,174	57,5	503,4	65,4	10 137	82	10,7
traditional insulation	1,226	8,2	71,5	9,3	1 440	37	4,8
windows (20%, single glazing)	0,170	58,8	515,3	13,4	2 077		
windows (20%, improved glazing)	**0,910**	**11,0**	**96,3**	**2,5**	**387**		
wood frame house							

Short homework

- compute the heat transfer coefficient *h* for a double glazing 10/10/4
- compute the embedded energy for a double glazing 10/10/4 and for a single glazing 5
- compute the energy pay-off time
- take into account boundary layer and radiative exchanges for the non-glazed facade
- improve the model by taking into account heat losses through ground and roof

Calculation of leakage

- Taking into account boundary layer on walls

	Rth	Leakage			fuel cost	grey Energy	
	$kW^{-1}m^2$	$W\ m^{-2}$	$kWh\ m^{-2}\ a^{-1}$	$MWh\ a^{-1}$	€/a	$kWh\ m^{-2}$	MWh
without insulation	0,174	57,5	503,4	65,4	10 137	82	10,7
without insulation (with limit layer)	**0,344**	**29,1**	**254,7**	**33,1**	**5 130**		
traditional insulation	1,226	8,2	71,5	9,3	1 440	37	4,8
traditional insulation (with limit layer)	**1,396**	**7,2**	**62,8**	**8,2**	**1 271**		
windows (20%, single glazing)	0,170	58,8	515,3	13,4	2 077		
windows (20%, improved glazing)	0,910	11,0	96,3	2,5	387		
wood frame house							

Wooden Frame House

Material	λ (W/K/m)	G. energy (kWh/m³)
Ordinary concrete	2,1	900
Cellular concrete	0,2	300
Hollow cellular concrete blocks 20 × 20 × 50 mm	1,15	410
Full brick	0,8	1 200
Hollow brick	0,4	675
Plasterboard BA13	0,25	1 450
Softwood	0,13	150
Wood particles panel	0,16	150
Insulating brick	0,11	
Straw	0,055	
Conventional insulation (polystyrene)	0,04	450
High performance insulation (polyurethane foam)	0,04	1 000
Cellulose wool	0,04	6 to 10
Glass	1	11 400
Immobile dray air	0,04	

Insulation – Cellulose wool

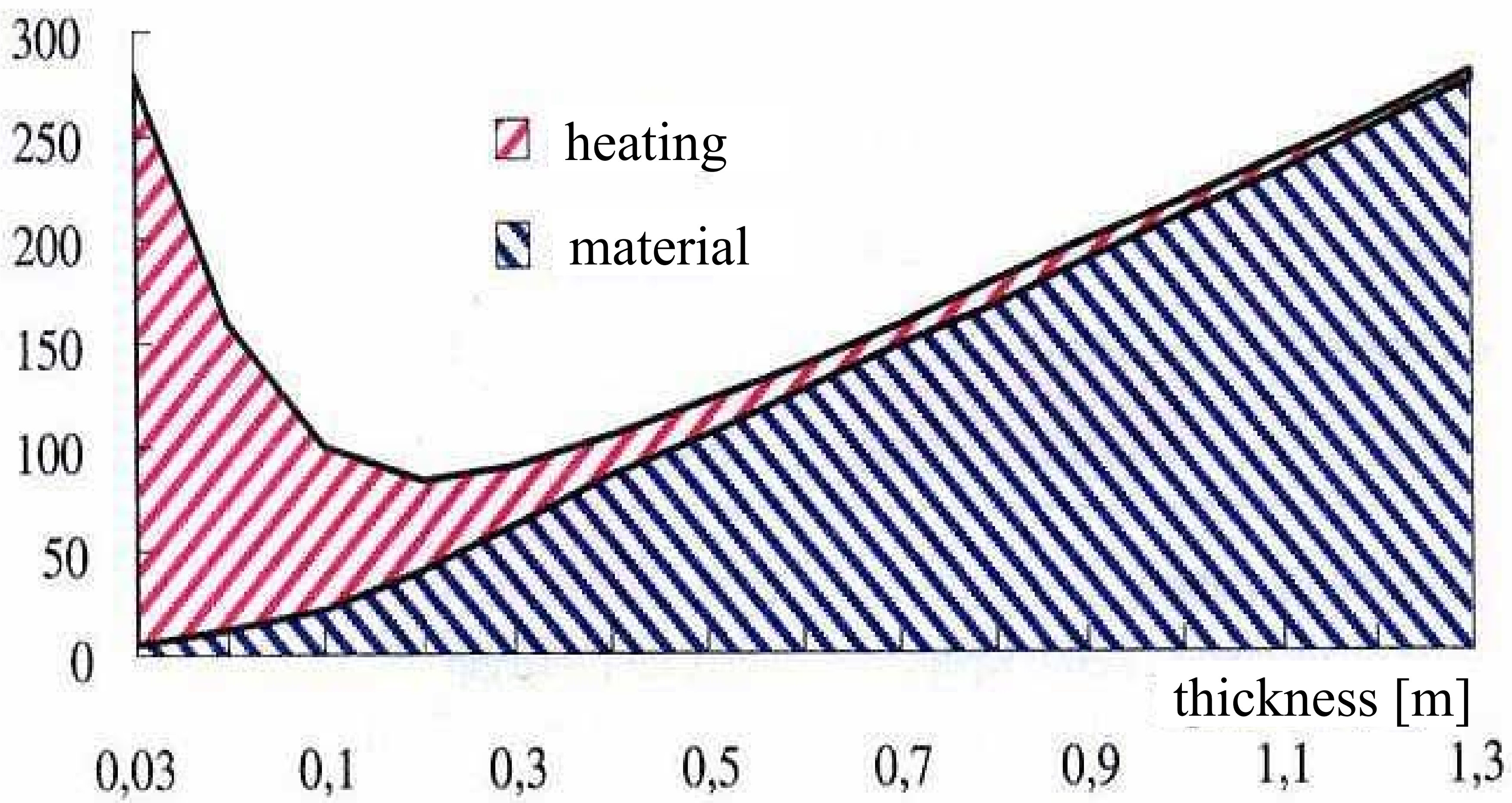
- Volume mass 20 kg m^{-3}
- Thermal conductivity 0,043 W/m/K
- Life time : 50 years
- Installation : In rolls, or by y direct injection/locking
- Grey energy: 6 to 10 kWh m^{-3}
- Price 130 € /m^3
- Produced from recycled paper
- Very good acoustic insulation

Calculation of leakage

- wooden frame house
- cellulose wool insulation

	Rth	Leakage			fuel cost	grey Energy	
	$kW^{-1}m^{2}$	$W\ m^{-2}$	$kWh\ m^{-2}\ a^{-1}$	$MWh\ a^{-1}$	€/a	$kWh\ m^{-2}$	MWh
without insulation	0,174	57,5	503,4	65,4	10 137	82	10,7
without insulation (with limit layer)	0,344	29,1	254,7	33,1	5 130	82	10,7
traditional insulation	1,226	8,2	71,5	9,3	1 440	37	4,8
traditional insulation (with limit layer)	1,396	7,2	62,8	8,2	1 271	37	4,8
windows (20%, single glazing)	0,170	58,8	515,3	13,4	2 077		
windows (20%, improved glazing)	0,910	11,0	96,3	2,5	387		
wood frame house	**3,57**	**2,8**	**24,5**	**3,2**	**496**	**16**	**2,1**

Optimal Insulating Thickness

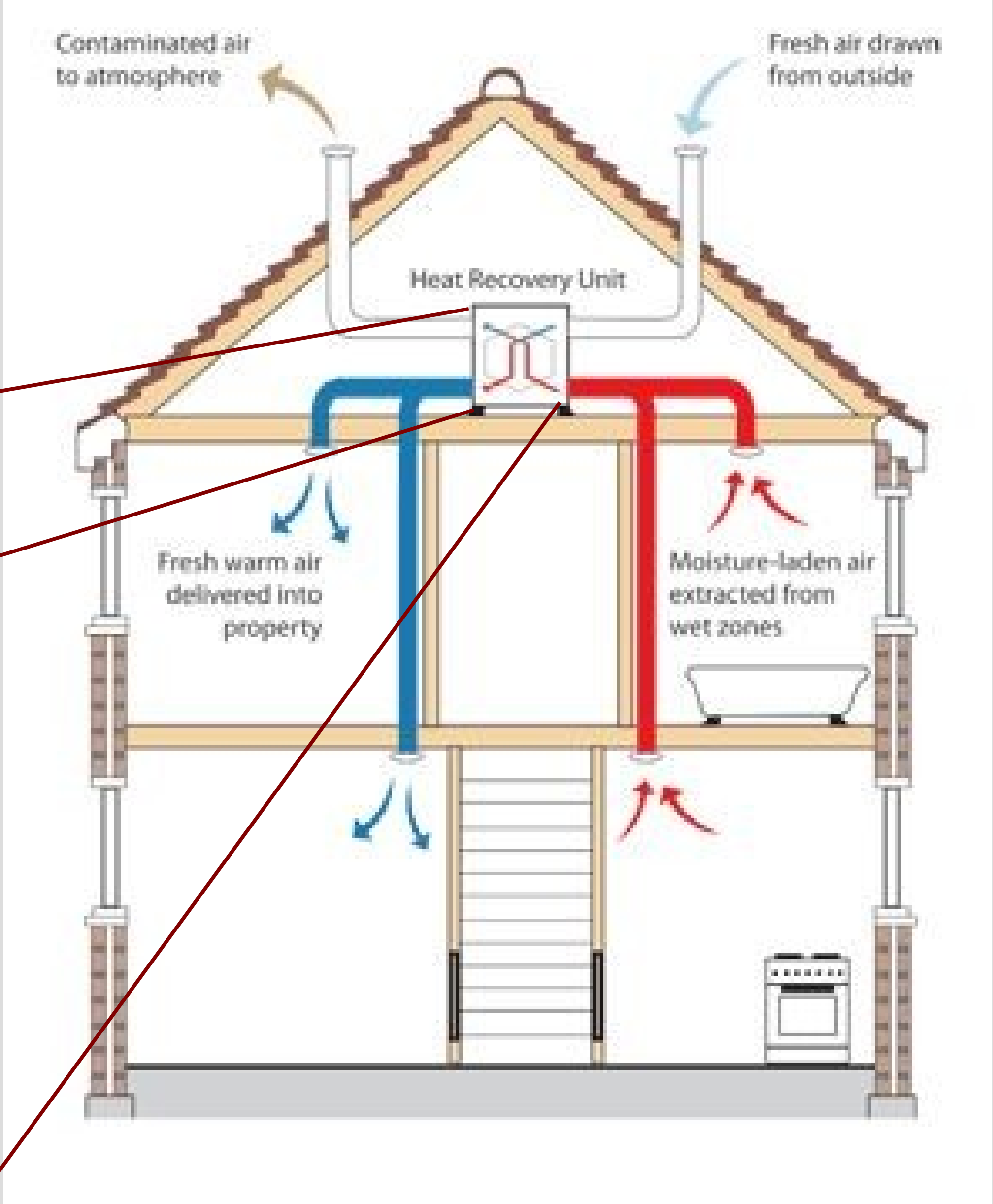


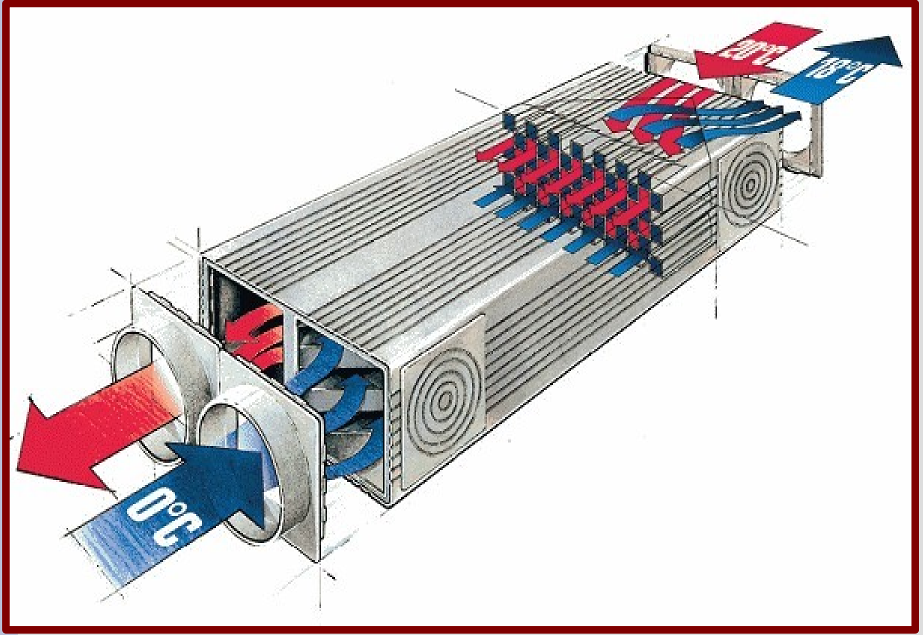
Cost of insulation versus thickness

Ventilation

Double flow air circulation with heat recovery

- New air injected in the living rooms
- Contaminated air extracted from the wet rooms

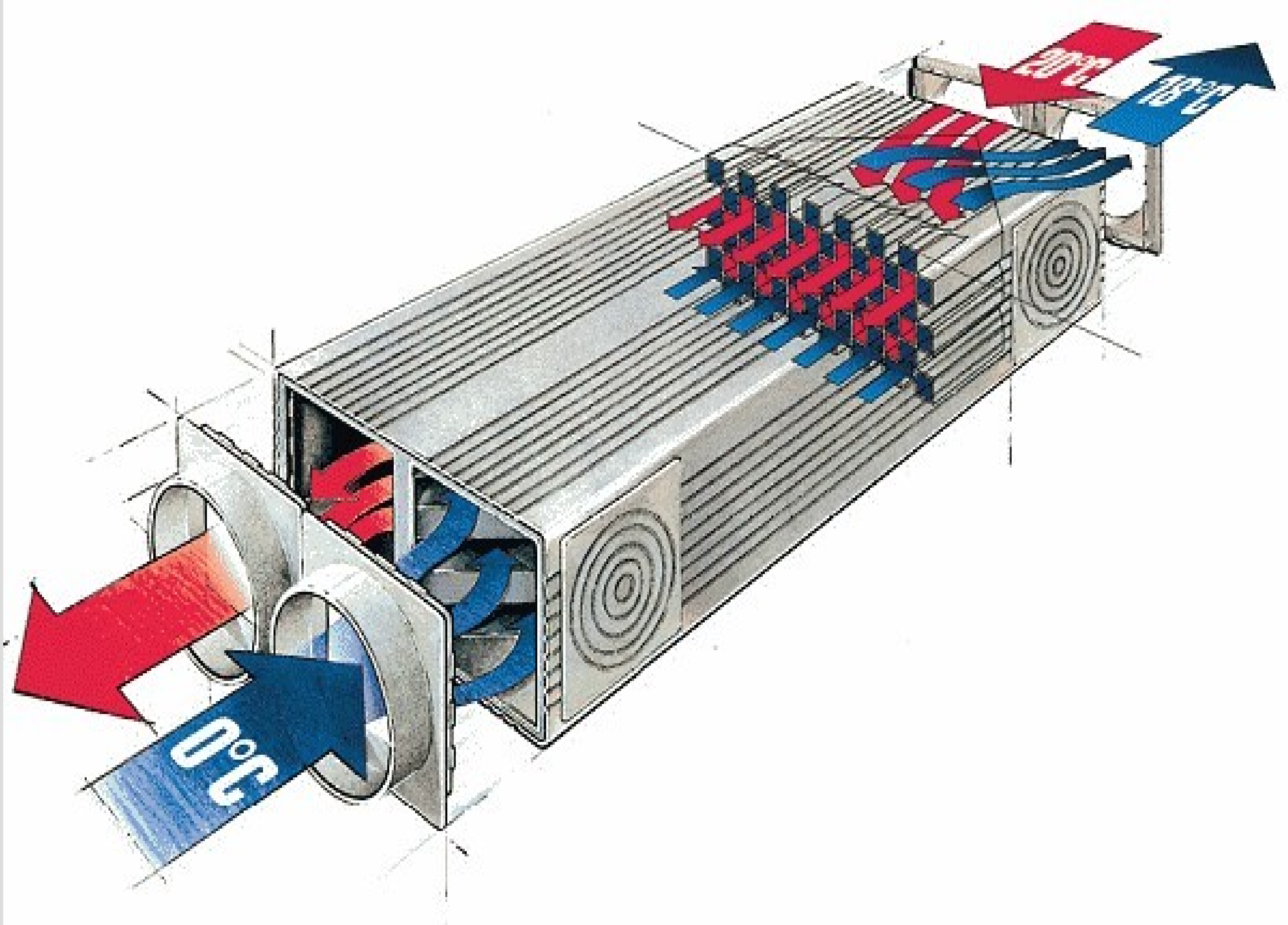




Counter-current exchanger

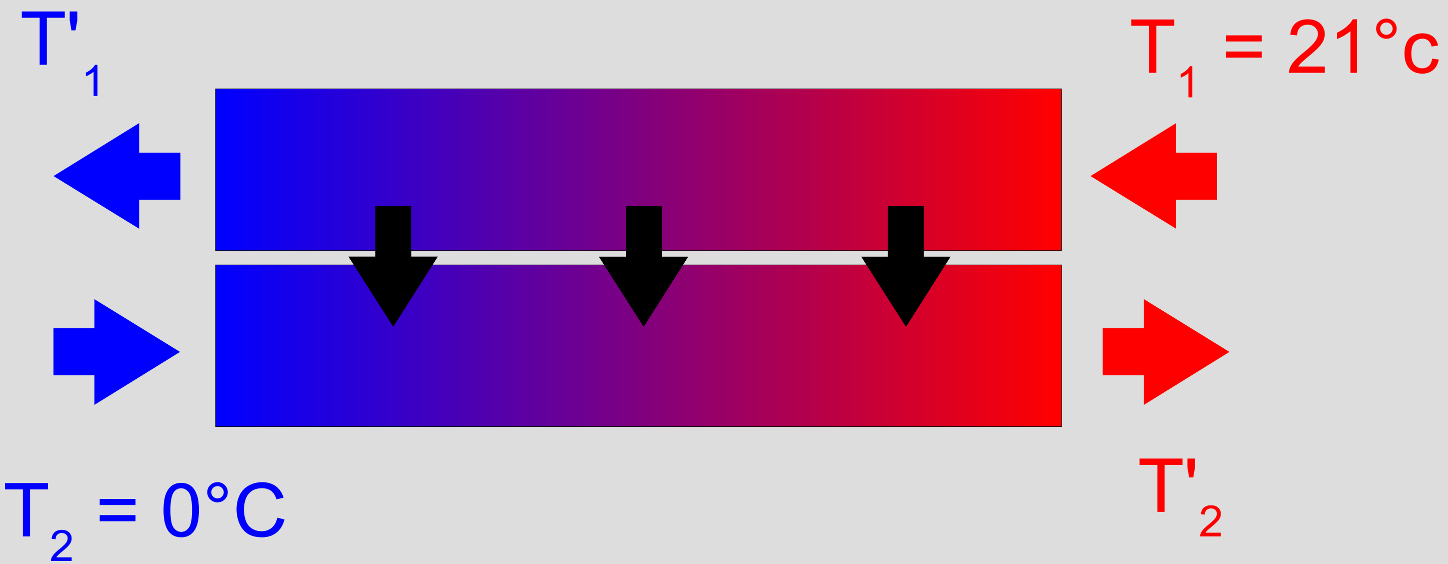
Double flow air circulation with heat recovery

- The incoming air is pre-heated from the exhaust air



Operation of the counter-current exchanger

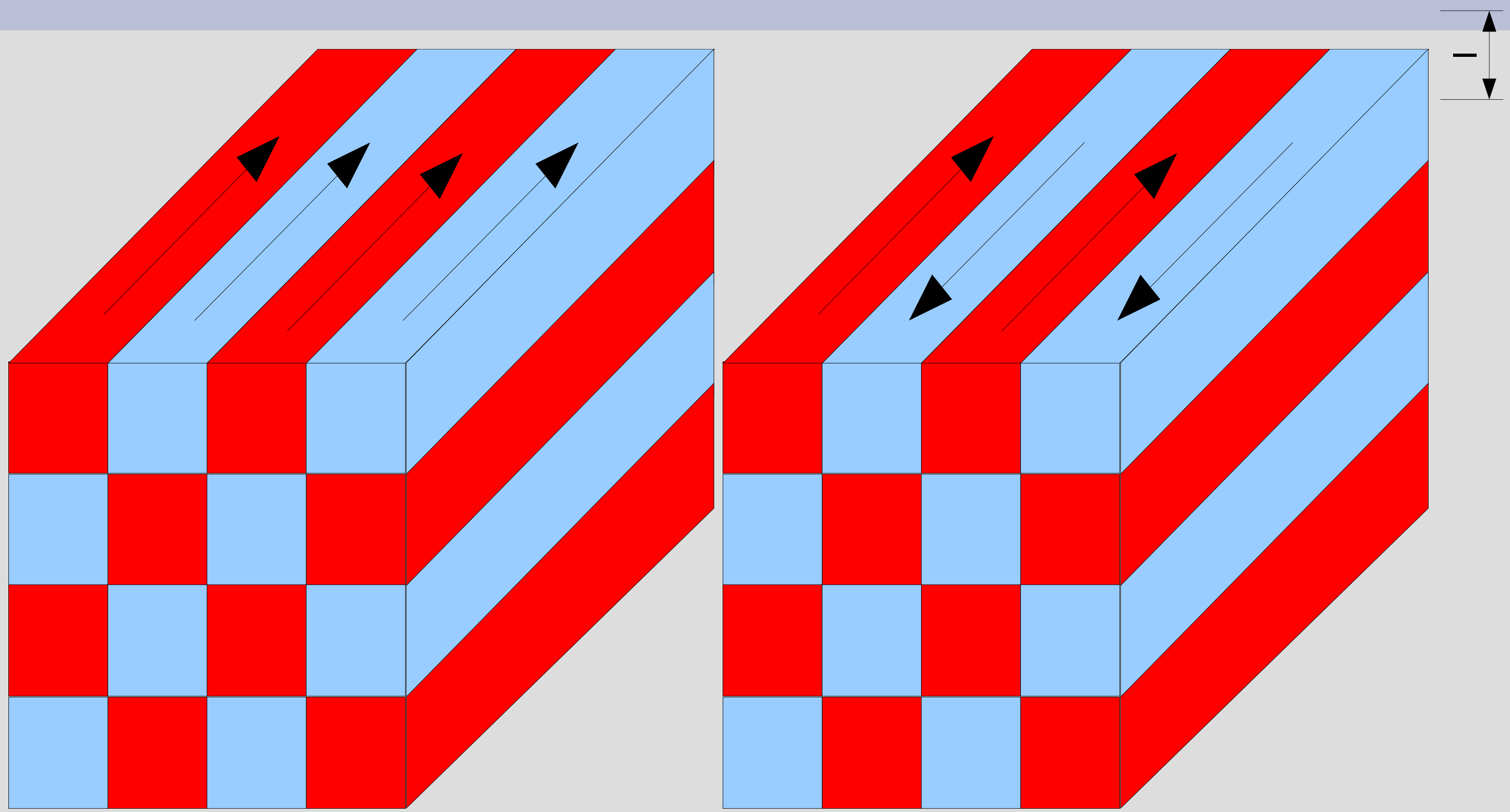
For an 100% efficient (infinitely long) exchanger, the temperatures are exchanged



- Transfers are made only if there is a temperature difference between the two sides => yield <1

$$Q_{\text{avail}} = C_p (T_1 - T_2)$$
$$Q_{\text{transfered}} = \eta Q_{\text{avail}} = C_p (T_1 - T'_1) = C_p (T'_2 - T_2)$$
$$T'_1 = (1-\eta) T_1 + \eta T_2 \quad \text{and} \quad T'_2 = \eta T_1 + (1-\eta) T_2$$
$$\eta = 0{,}8 \quad \Rightarrow \quad T'_1 = 4.2\,°\text{C} \quad \text{and} \quad T'_2 = 16{,}8\,°\text{C}$$

Cell heat exchanger



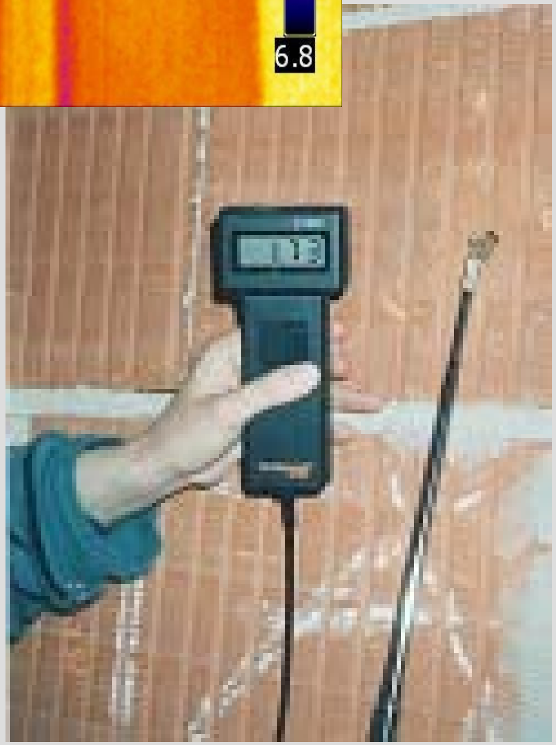
- Exchange area multiplied by $2\times(n-1)$
- Here n= 50 $\Delta A = \underbrace{2\times(n-1)\times l}_{L_A}\times\Delta x$

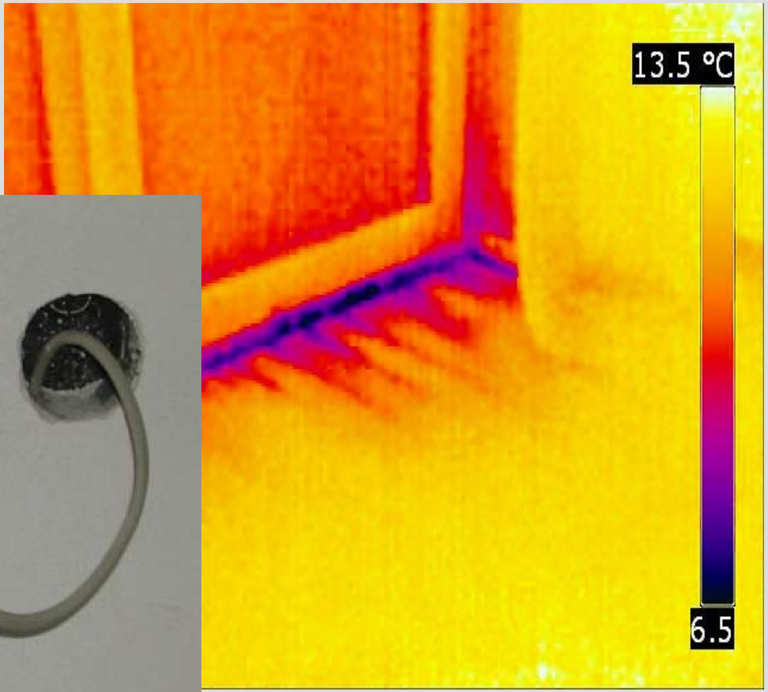
Leakage measurements

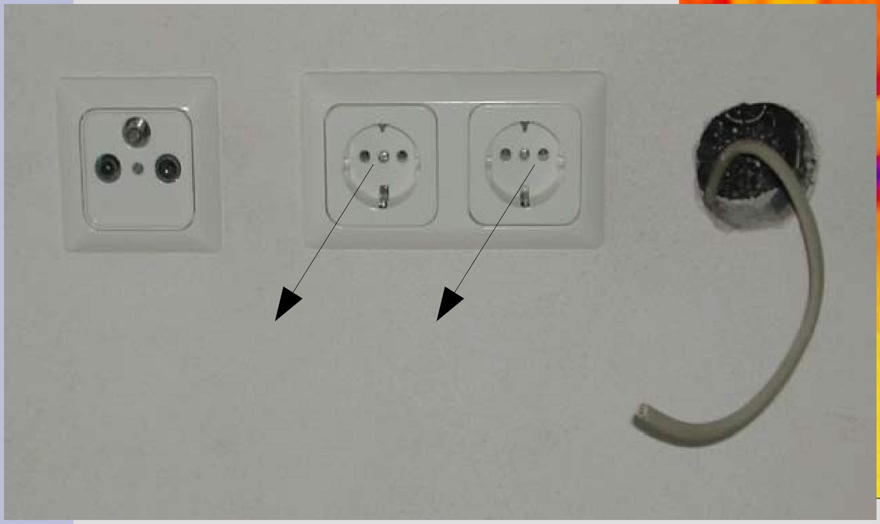
- "Blowerdoor" measurement (infiltrometry)
  - Overpressure building
  - Insulate natural orifices
  - Tracing leaks using smoke
  - Thermography (Cold air inlets)
  - Measurement flow for a fixed overpressure

Air-tightness – Common problems

- Seals, cracks
- Frames, thresholds
- Cables, plugs, hoses



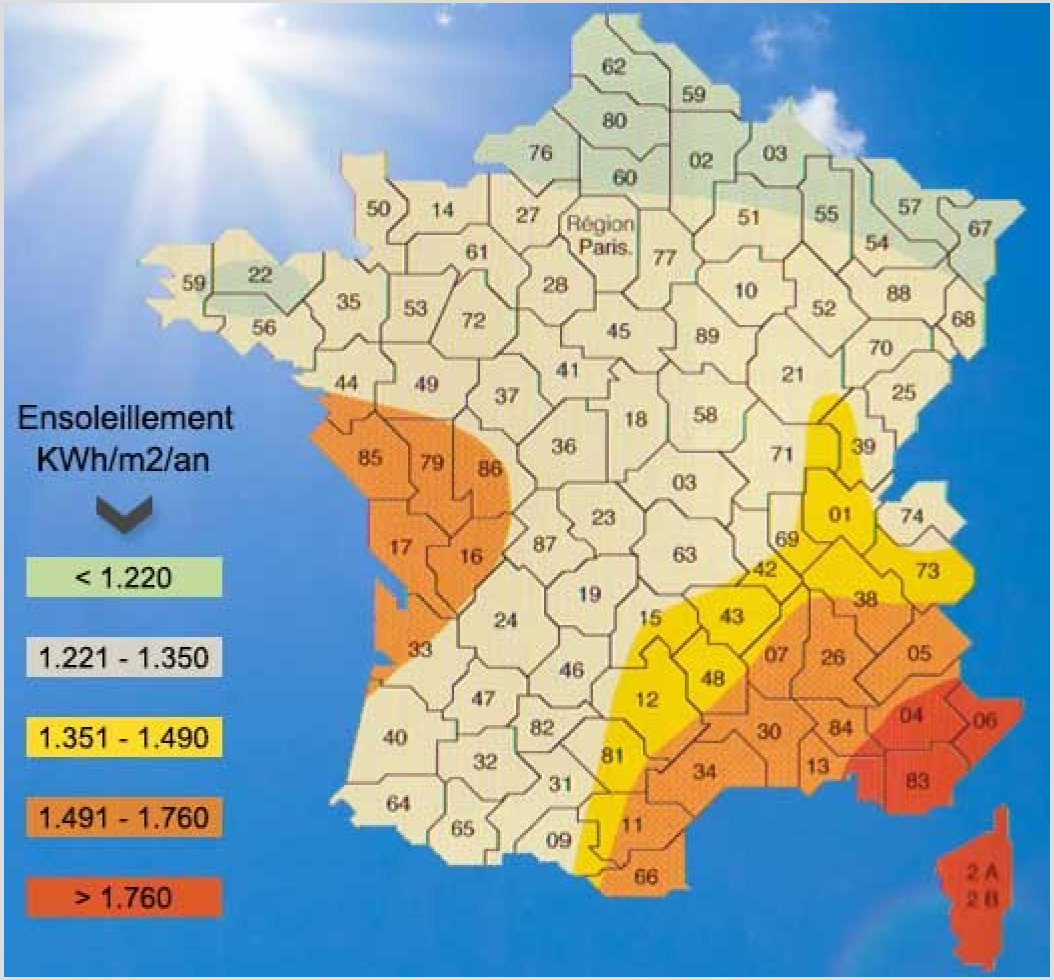




External energy incomes

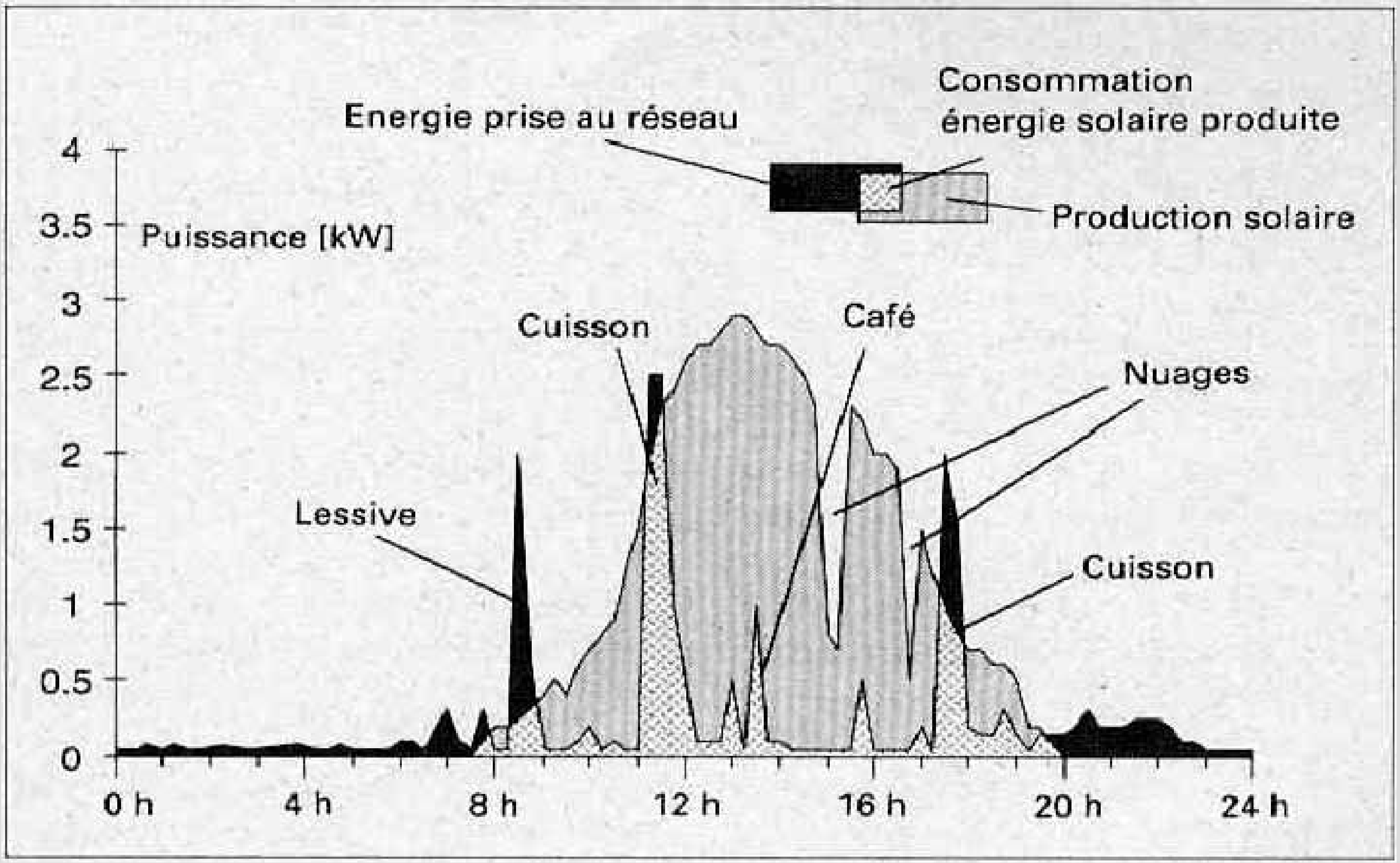
Average solar illumination

- Solar constant:
  - ▸ 1368 W/m^2
    → 12 500 kWh/m^2/yr
- Temporal average
  - ▸ 342 W m^2
    → 3000 kWh/m^2/yr
- Atmospheric absorption and clouds (~50%)
  - ▸ 1000 to 1500 kWh/m^2/yr
  - ▸ ~ 1000 h under normal incidence with the nominal flux of 1368 W/m^2



Solar Photovoltaic

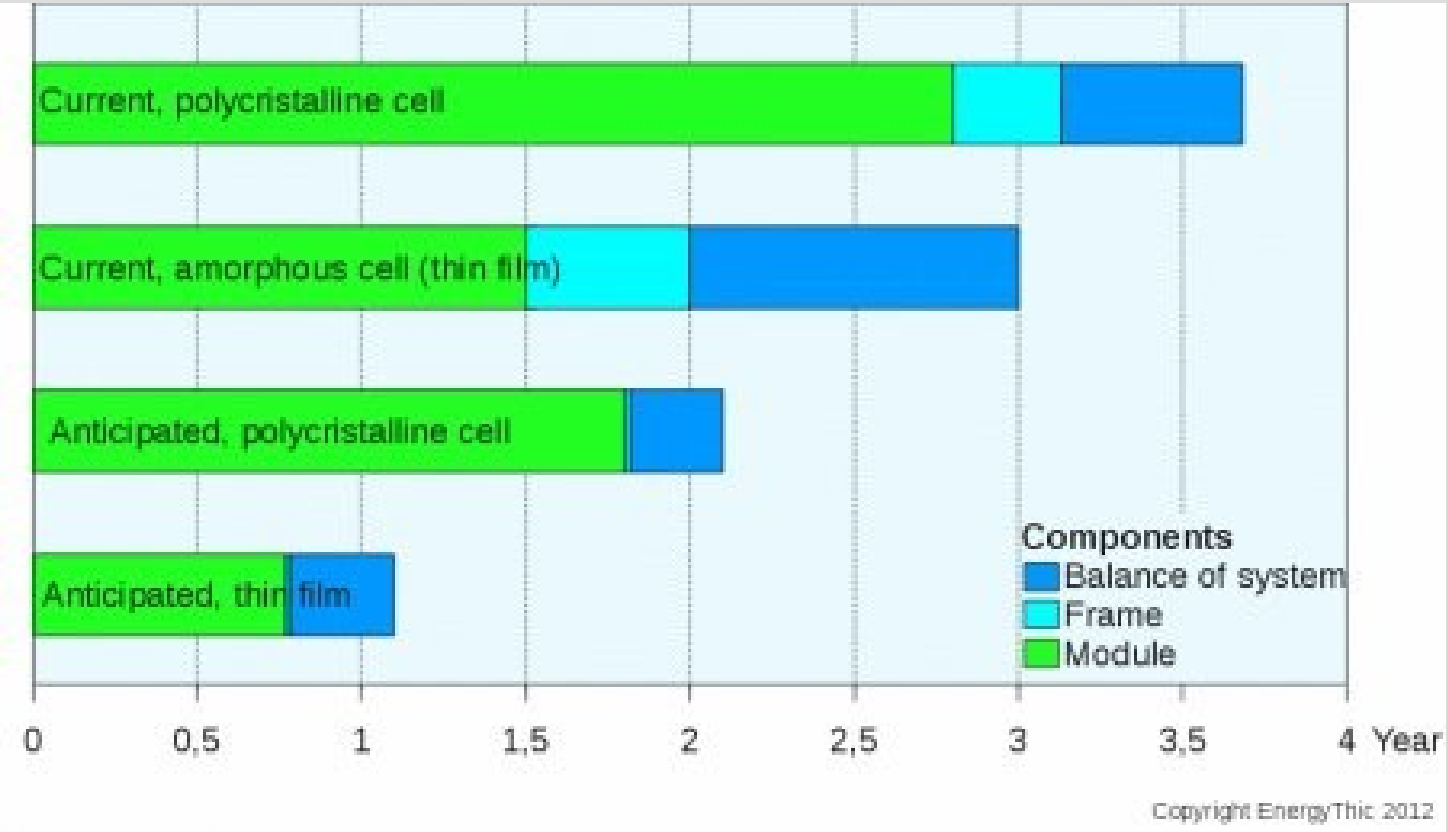
- Inadequacy of solar resources to domestic needs
  - Connection to the network needed



Source Cythélia

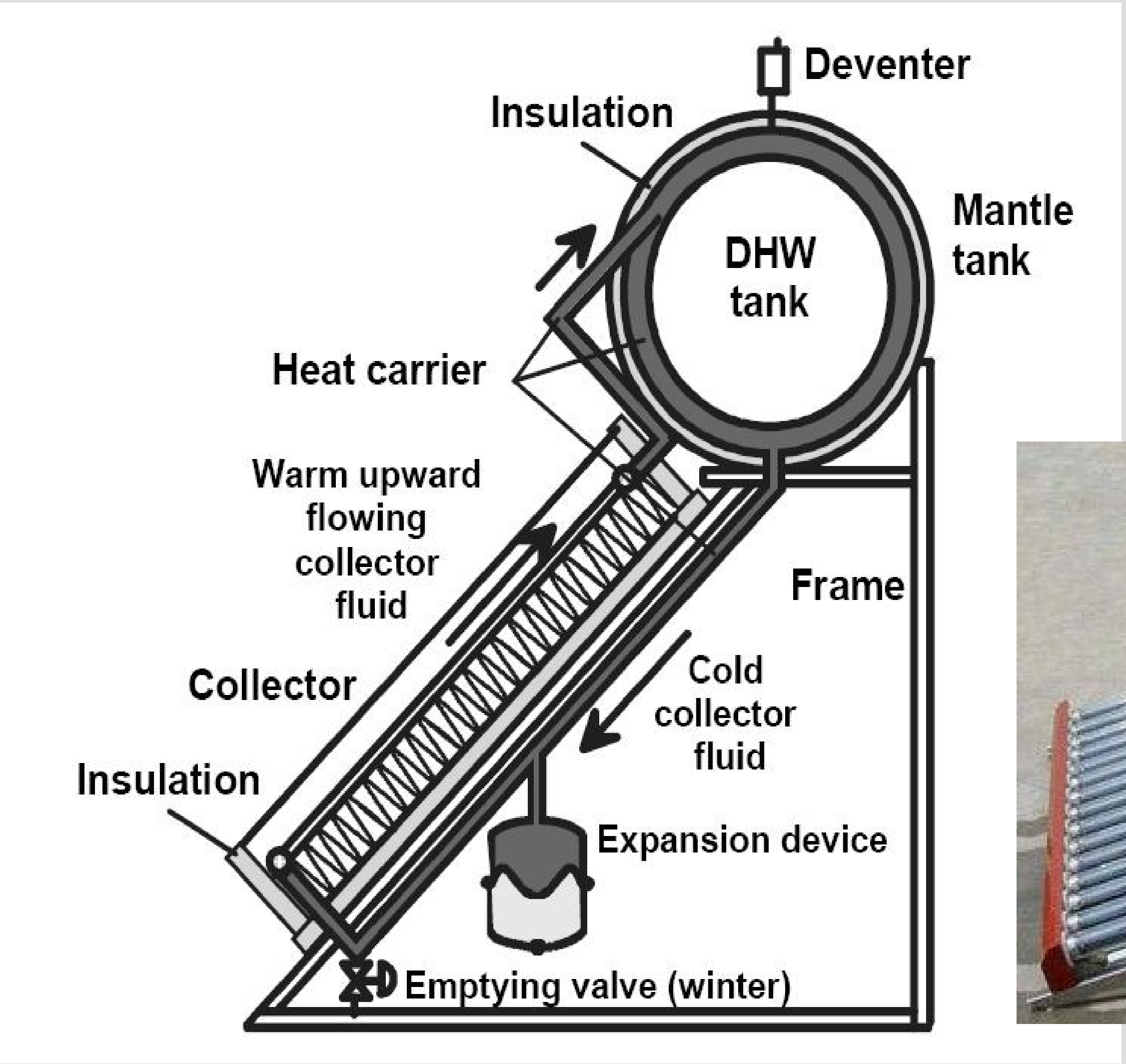
Grey energy of photovoltaic cells

- Gray energy incorporated in photovoltaic systems, measured in years of production, using current and foreseeable techniques in the near future.
- According to NREL, the United States Department of Energy



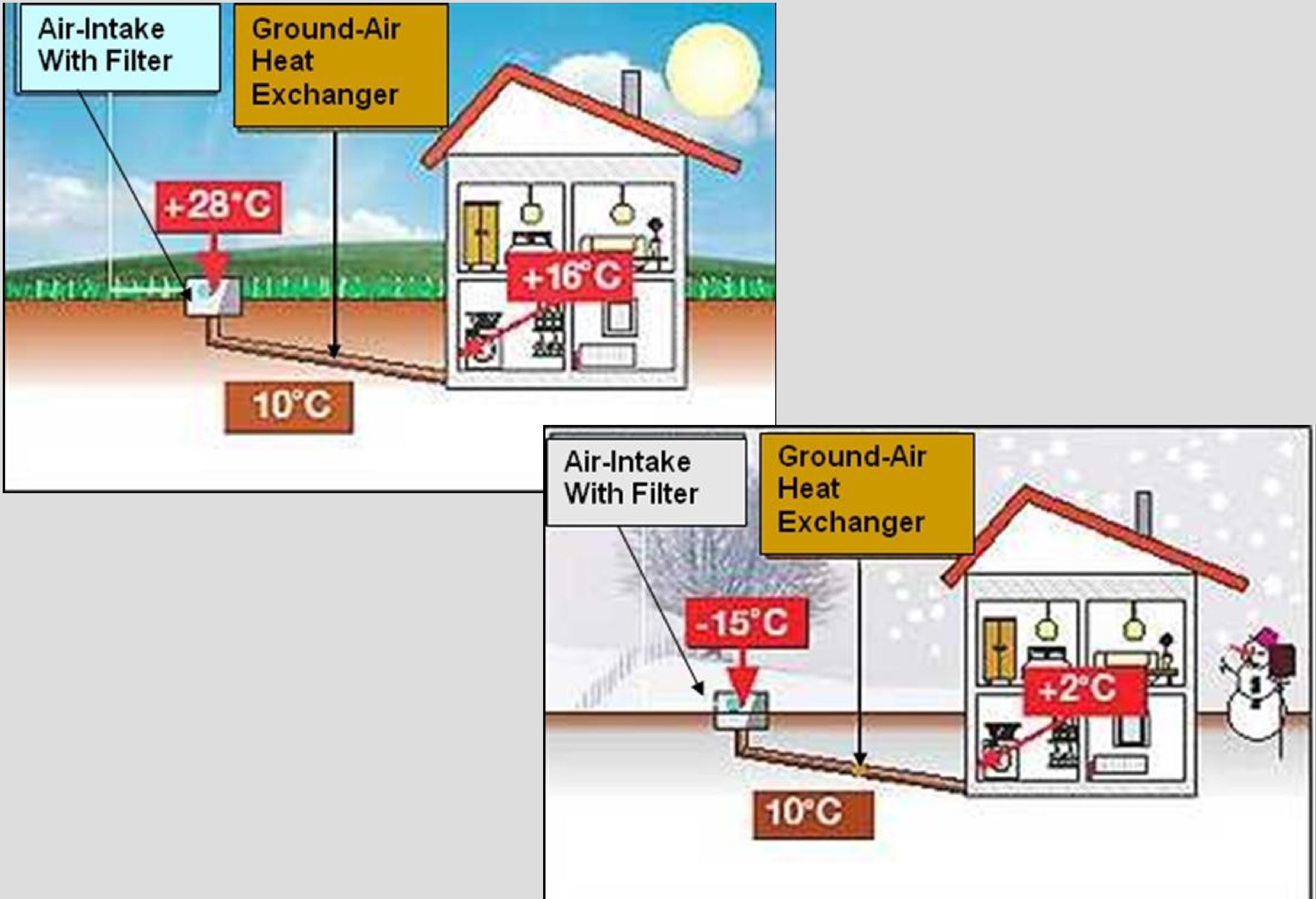
Domestic hot water system

- Natural circulation (without pump)



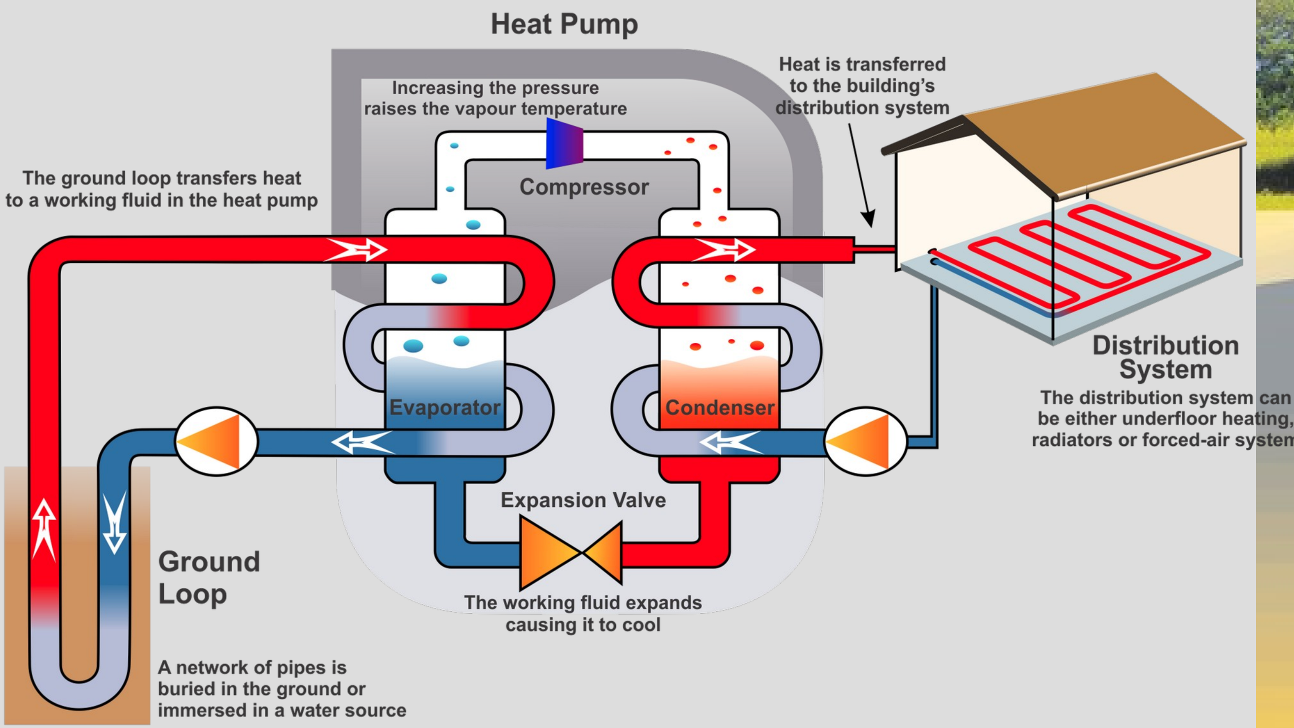
Domestic hot water system

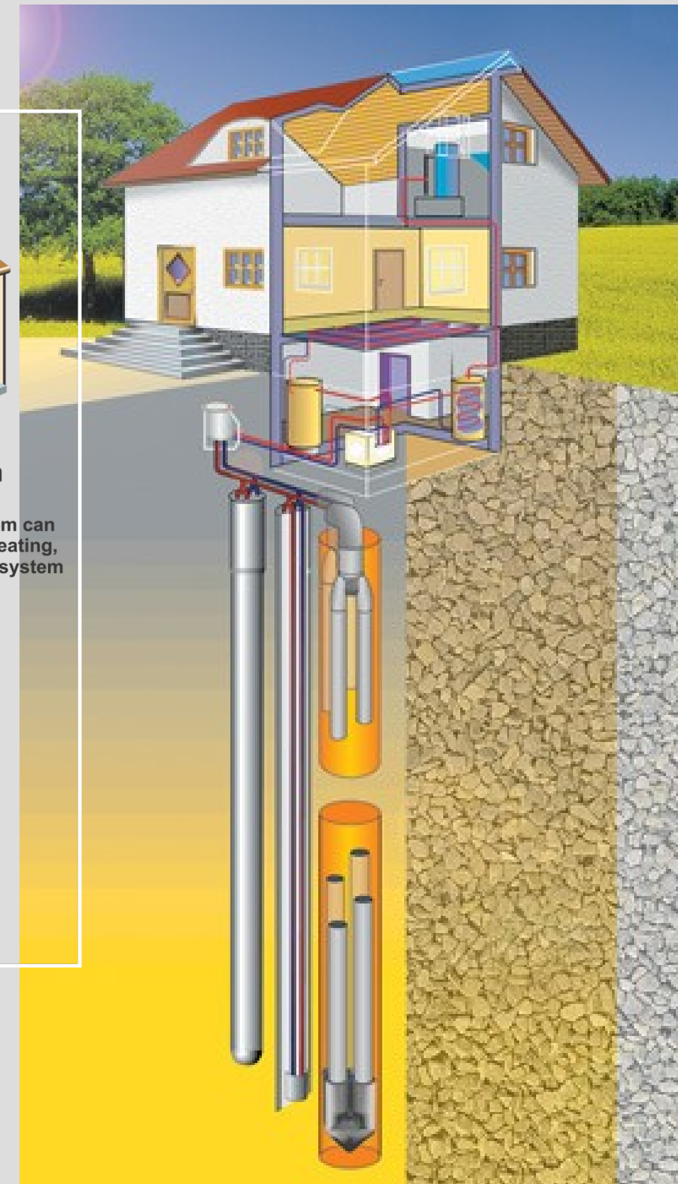
Provençal / Canadian well



Provençal / Canadian well

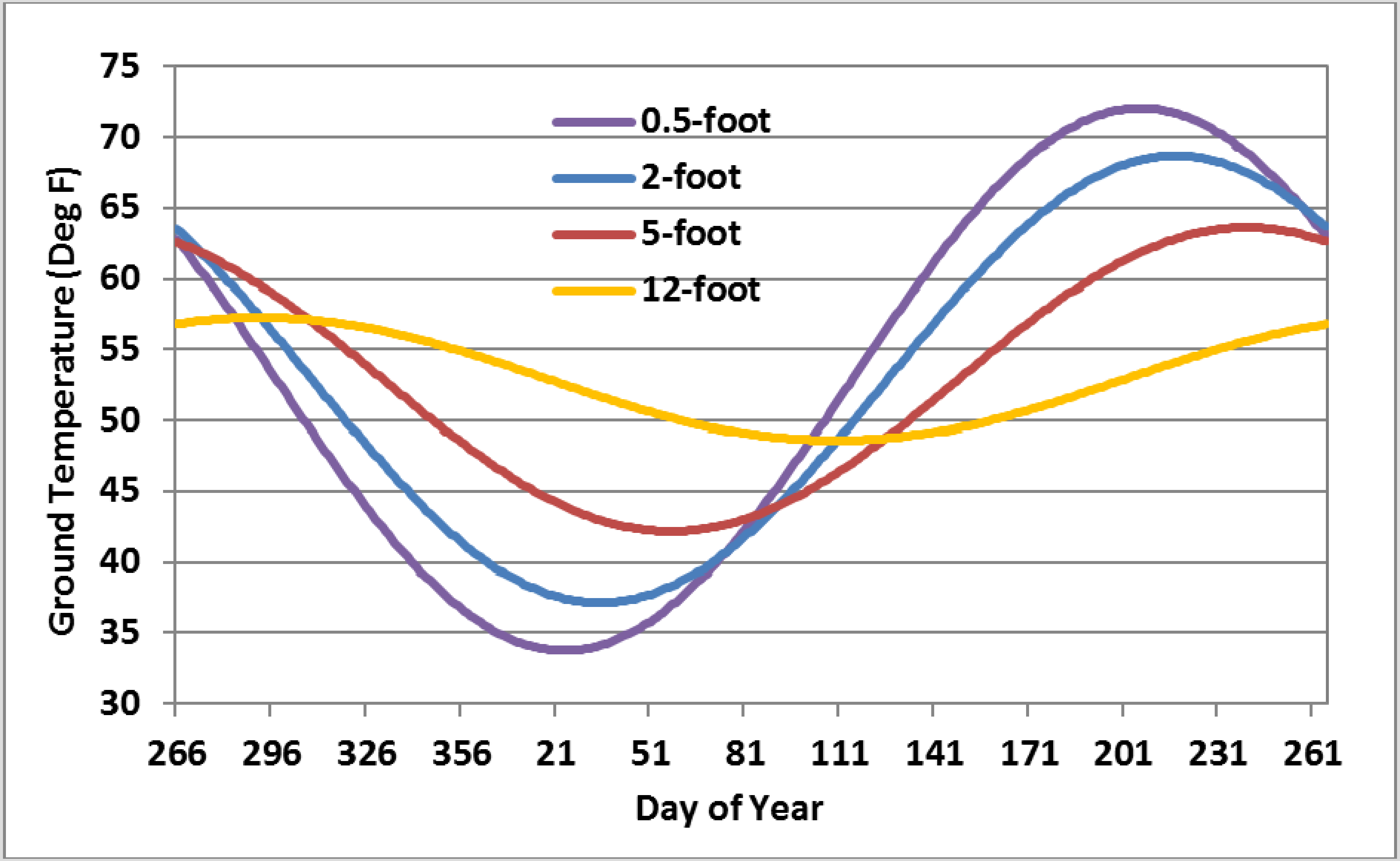
Geothermal Heat Pump



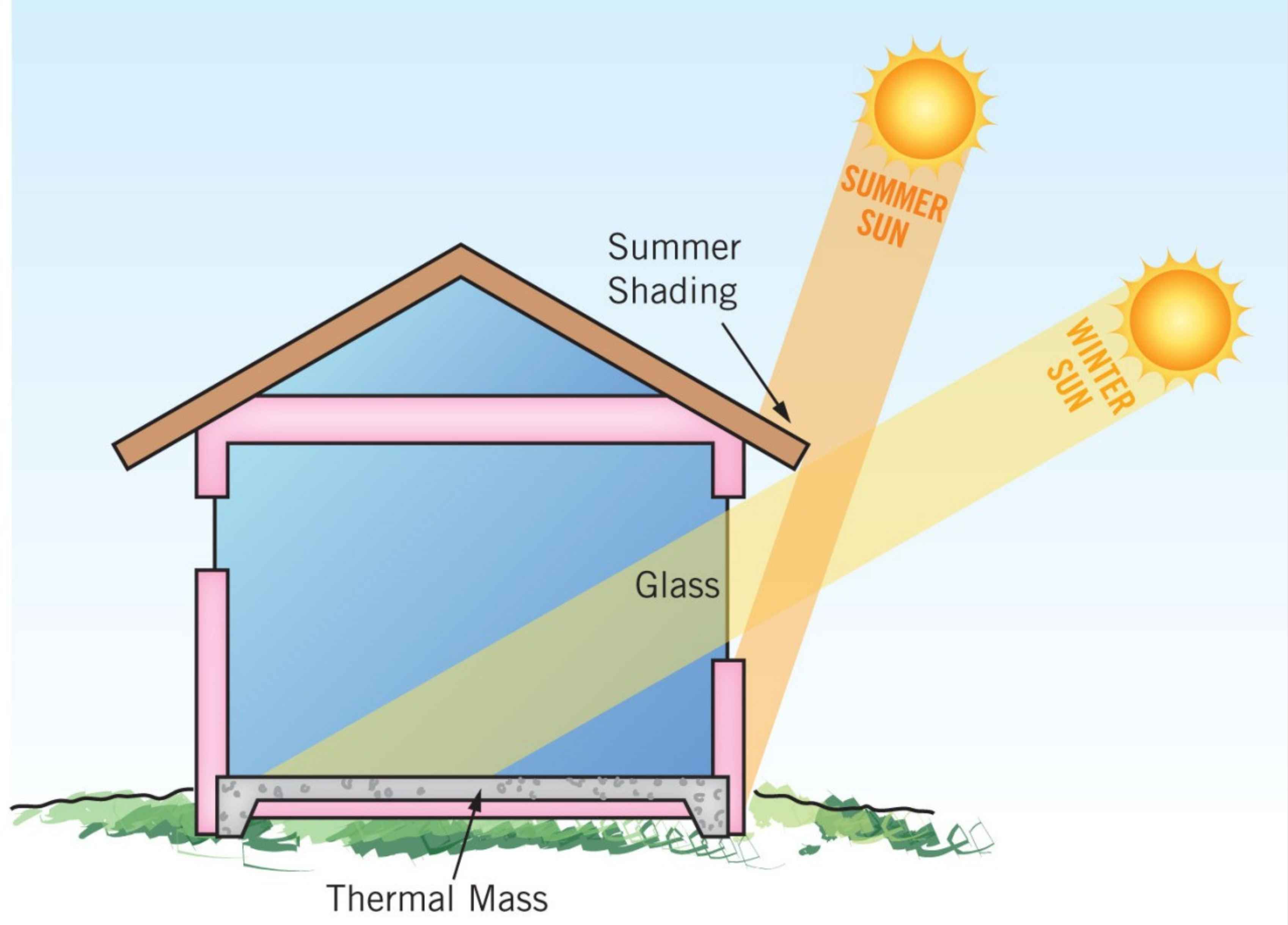


Ground temperature

- Decreasing amplitude, delayed peaks



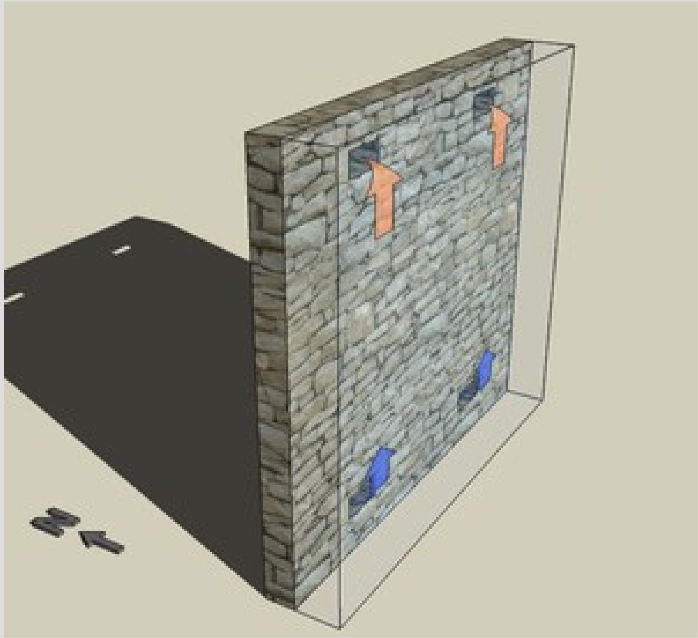
Passive solar

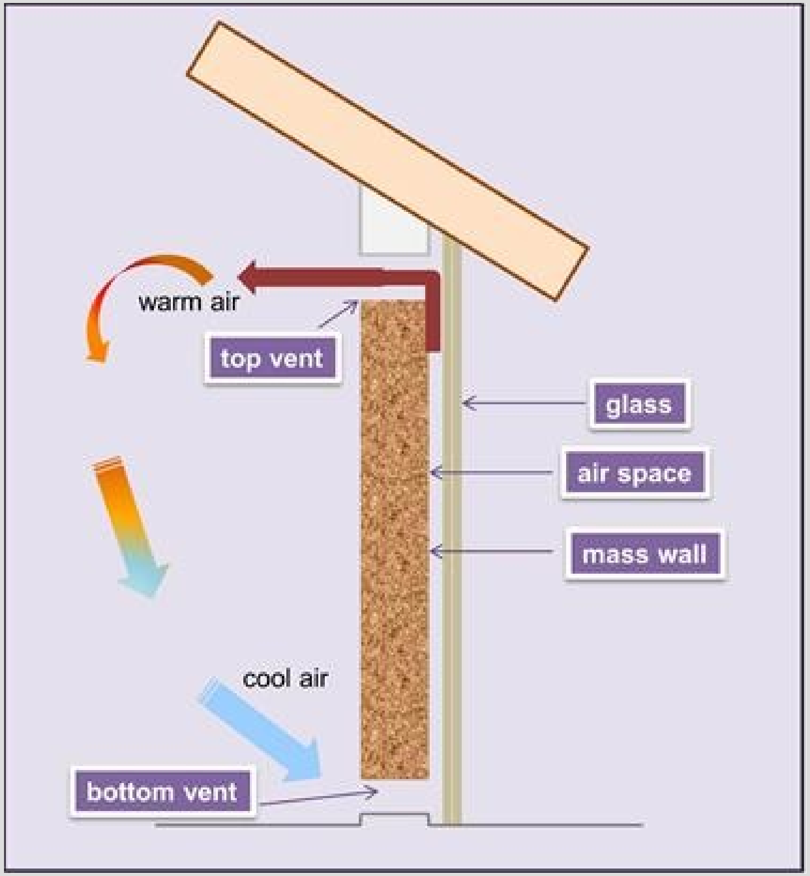


Passive Solar – Trombe wall

- Greenhouse effect
- Airflow between a glazing and the wall
- Wall with high thermal inertia → provides calories at home at night (regulation by management of flaps)
- Optimum Thickness:

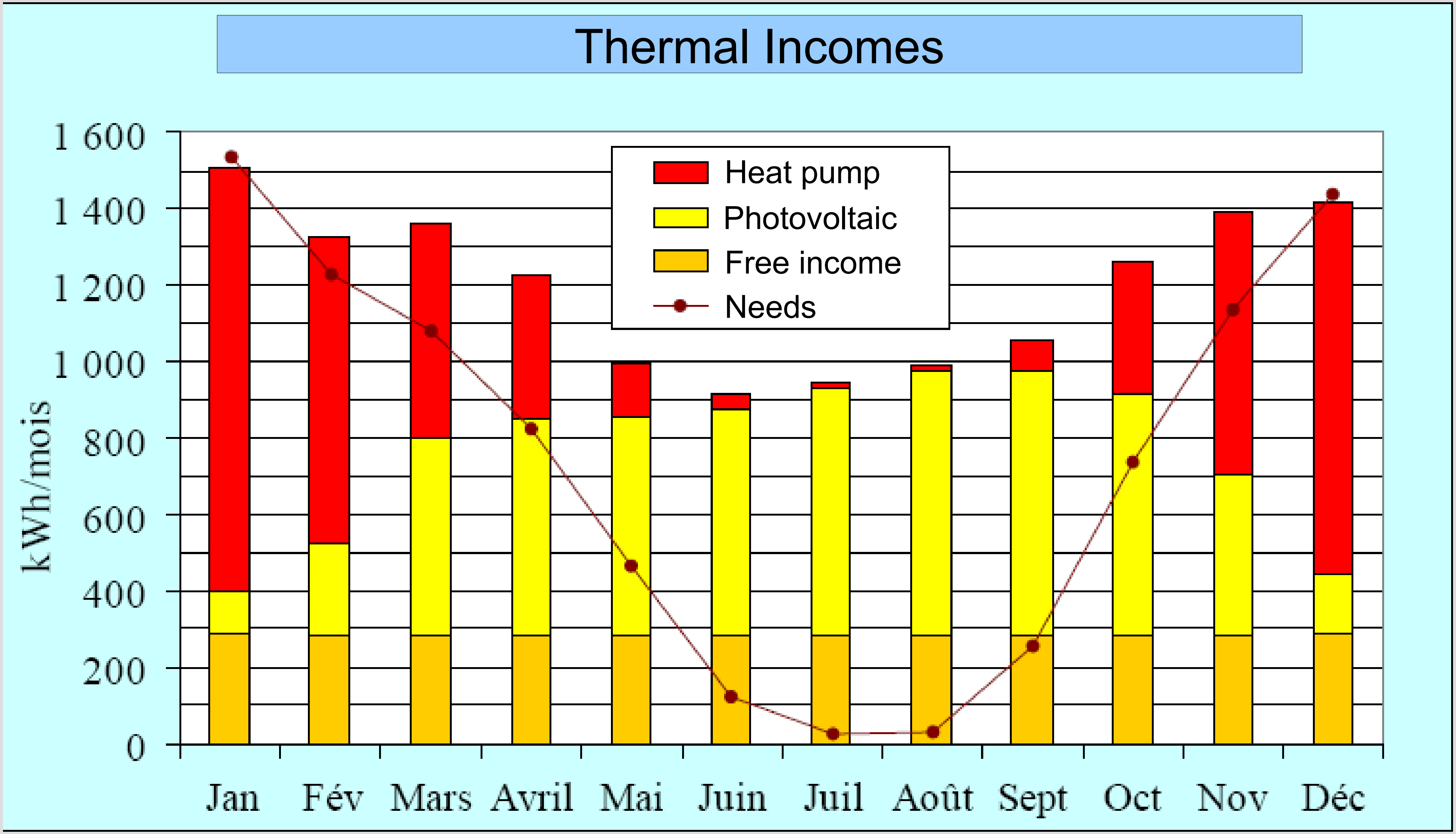
  20 to 30 cm





Balance

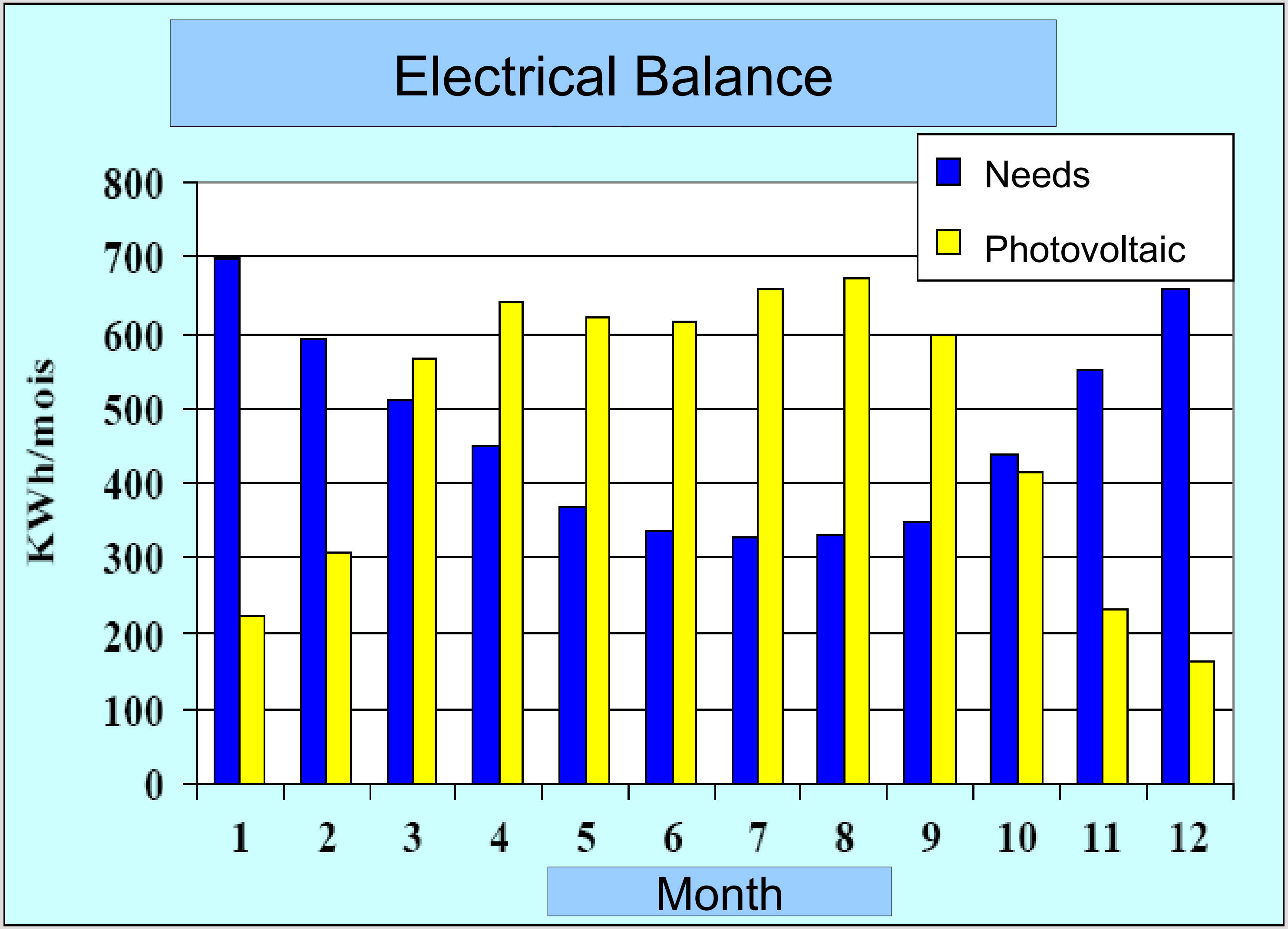
Thermal Balance



Source Cythélia

Electrical Balance

- It is possible to have an electrical balance ~ neutral over the year, but not month by month



Financial Balance (Cythélia)

- Additional cost ~ 40 000 € (per 100 m²), dominated by photovoltaics
- Covered to ~ 60% through grants
- Annual Savings ~ 1000 € - Profitable over 20 years thanks to subsidies!

Investissements (euro)	Reference	Option 2	Option 4
	Parpaing+isol stand	Briques monomur	Ossature bois
Toiture	1 269	4 628	5 869
Maçonnerie	11 454	12 823	10 773
Plancher	5 541	5 341	6 400
Vitrage	785	942	942
Total isolation passive	**19 049**	**23 733**	**23 983**
Chauffage actif (kWh /m² .an)	75	51	40
Electr (kWh /m² .an)	60	39	26
Chaudière gaz	2 000	0	0
Plancher chauffant	5 000	5 000	0
PAC air extrait / eau	0	6 000	0
PAC eau/eau	0	0	0
Capt horiz / Puits canadien	0	0	1 000
Forage vertical	0	0	0
PAC air extrait / air	0	0	5 000
Système PV	0	39 750	39 750
Total chauffage / elec actif	**7 000**	**50 750**	**45 750**
TOTAL brut	**26 049**	**74 483**	**69 733**
Surcoût brut	**0**	**48 434**	**43 685**
Subventions industriels			
Subvention Département	0	0	0
Subvention Région	0	7 950	7 950
Subvention ADEME	0	20 160	20 160
TOTAL Aides	**0**	**28 110**	**28 110**
TOTAL après subvention	**26 049**	**46 373**	**41 623**
Surcoût net	**0**	**20 324**	**15 575**

The Positive Energy House