Low Exergy Theory

Hansjürg Leibundgut and Forrest Meggers

Low Exergy Building Design Workshop

Tues, 25.01.2011

09:00	Introduction of exergy (Prof Dr Hansjürg Leibundgut)
09:20	Exery Theory and Background (Forrest Meggers)
10:00	Zero Emission Architecture (Prof Dr Arno Schlueter)
10:40	Break/Disscussion
11:00	Singapore Building Practices (Prof Dr Chandra Sehkar)
11:40	Round Table Discussion "How can exergy theory be applied in Singapore?"
12:00	Lunch Break

SEC Future Cities Lab: Module 1 - Low Exergy

A brief history of Building Systems

until 1900 buildings were not affected by the industrial revolution
almost no heating, no electricity, no running water... extravagances

WW1 brought a combustable energy source market for all temperatures

1870 and 1940 a second revolution took place
introduction of electricity into industry-> civil engineers-> dams and caverns

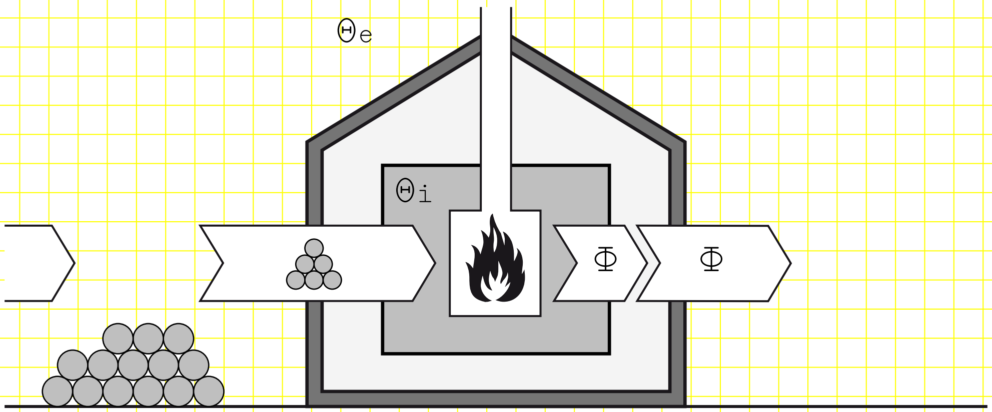
After WWII the Alpine fortress builders moved on to exploit hydro-power

In 1970 Energy was just a word in physics

1950's all buildings got central heating with cheap oil burners
    -high temperature heating systems (70-90 deg C)

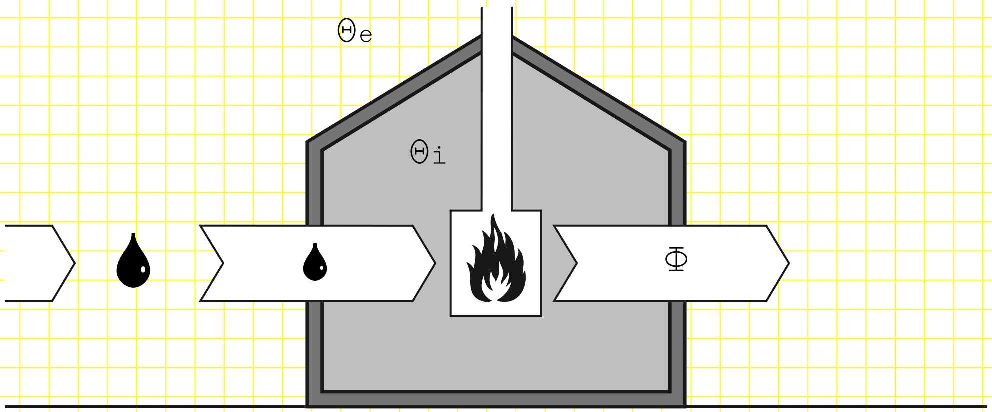
Oil crisis of 1973 brought the first recognition of the energy supply
-diversification of primary energy source
-energy savings programs were setup (1984 CH first regulation)
    -wrote in this regulation that the max temp is 60 degrees
-best windows -> 2 W/m2 K

Evolution of Building Systems



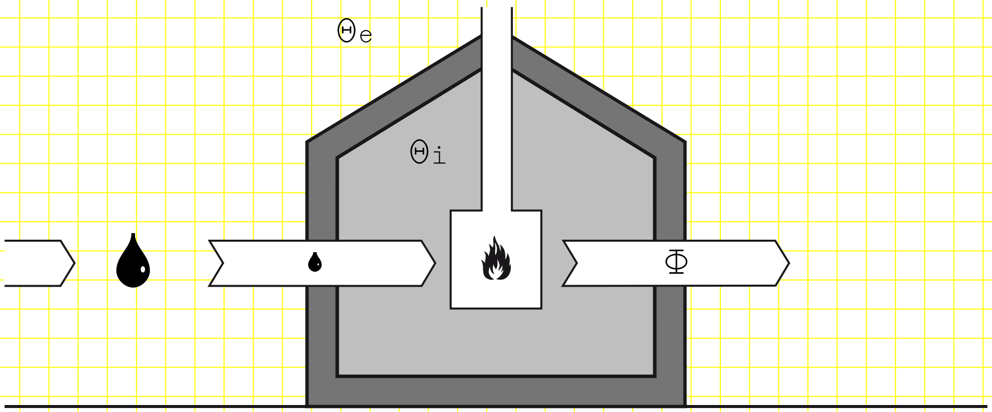
In the beginning...
Small houses heated by biomass

Evolution of Building Systems



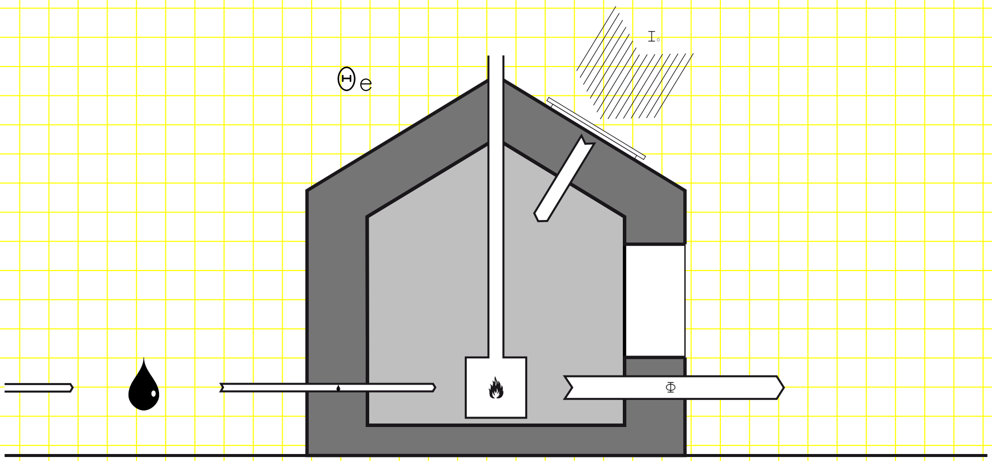
Discovery of fossil fuels...
Energy becomes abundant, size increases

Evolution of Building Systems



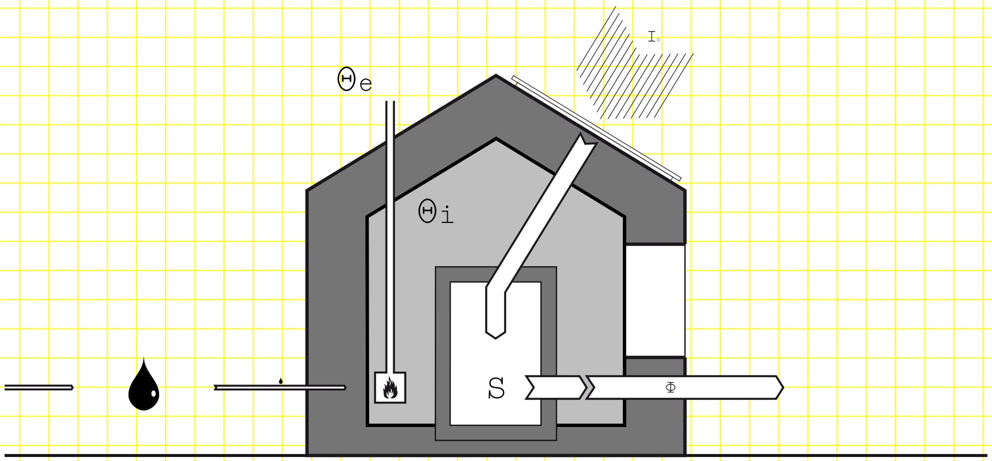
Resource limits are recognized...
Insulation is implemented

Evolution of Building Systems



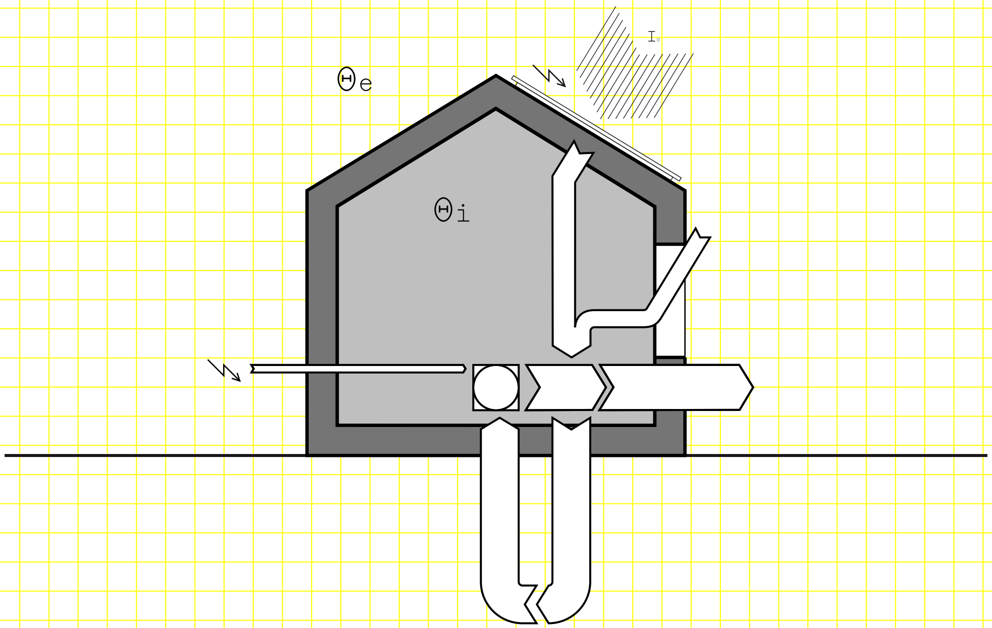
High performance desire...
Attempts to eliminate losses

Evolution of Building Systems



Potential of storage...
Increase in flexibility of design

Evolution of Building Systems



New LowEx paradigms...

Extract free energy with technology

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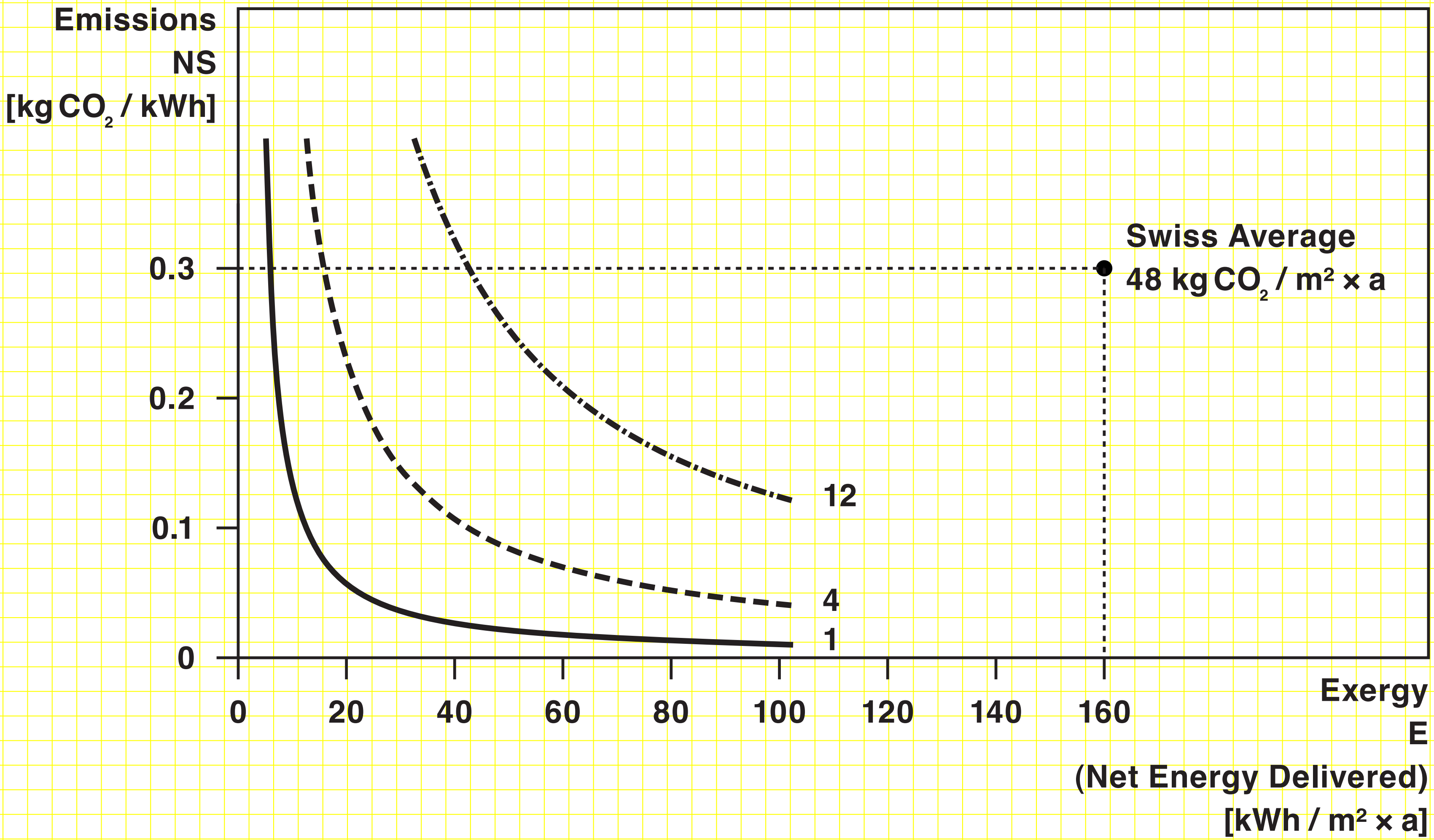
Low Exergy Paradigms

1) Energy is not just energy, as it also has an inherent quality: Exergy

2) There is no energy shortage, rather an energy overflow

3) Active technology is better than passive technology

Low Exergy Paradigms Goal



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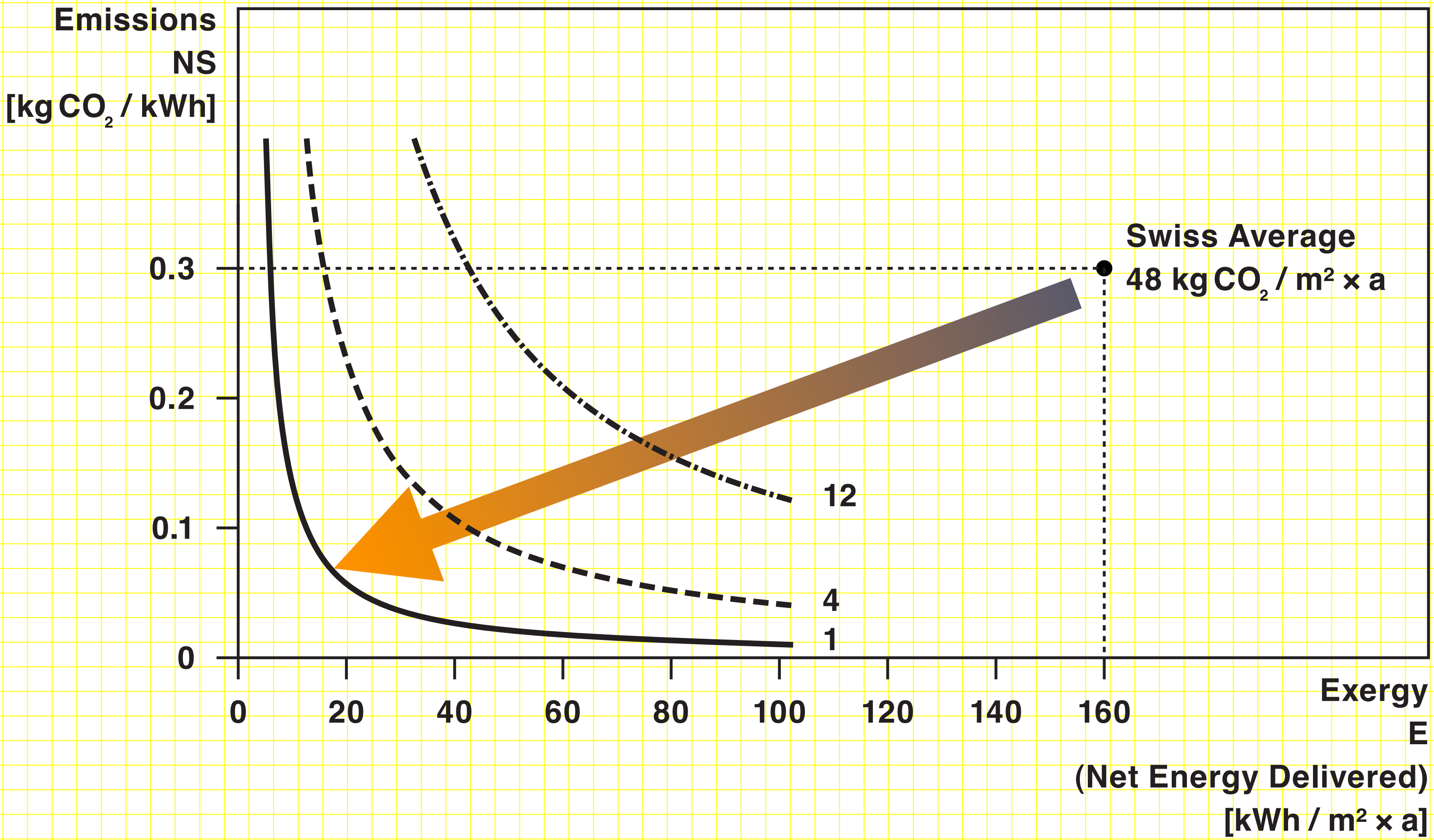
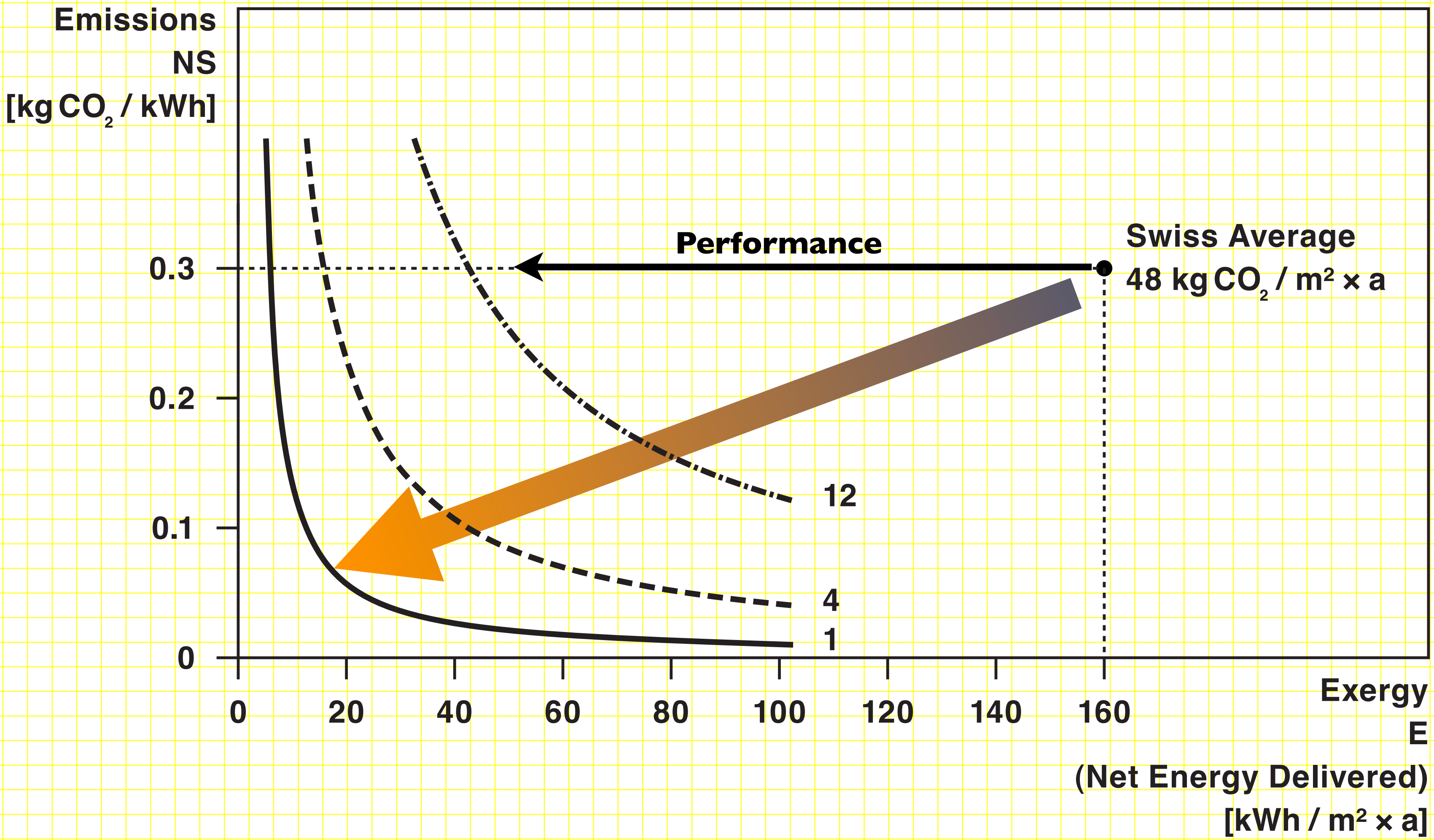
Low Exergy Paradigms Goal



Low Exergy Paradigms Goal



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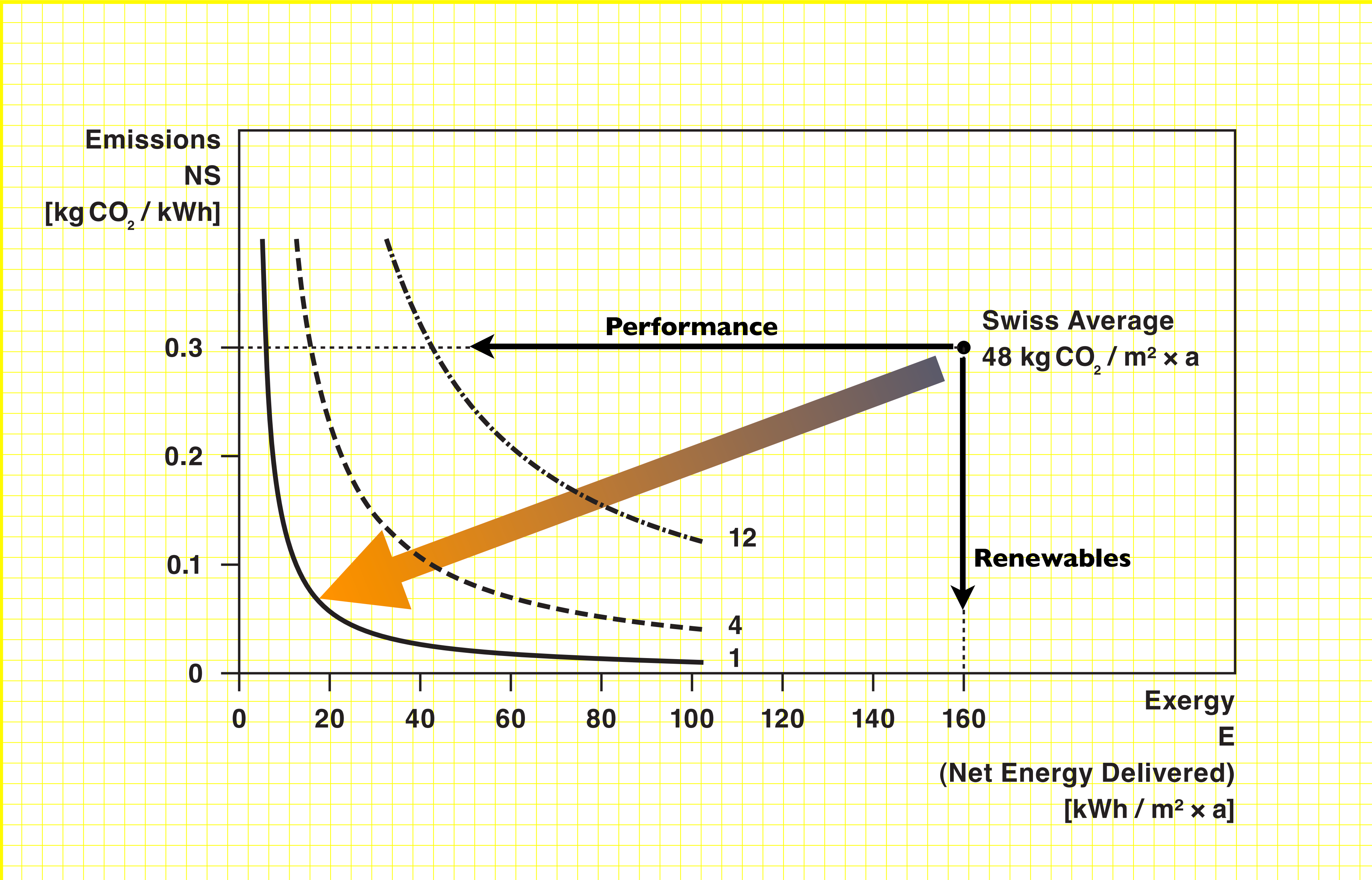
Low Exergy Paradigms Goal



First Paradigm

1) <u>Energy is not just energy, as it also has an inherent quality: Exergy</u>

2) There is no energy shortage, rather an energy overflow

3) Active technology is better than passive technology

First Paradigm: Energy & Thermodynamics

First Law of Thermodynamics says that energy is conserved

Energy In = Energy Out

But if energy is conserved through every system, what do we mean by the phrase "Energy Loss" or "Energy Waste"

Even when heat is "lost" from a building, the 1st Law energy balance is still upheld because the outside gains that exact amount of energy... there is no "loss"

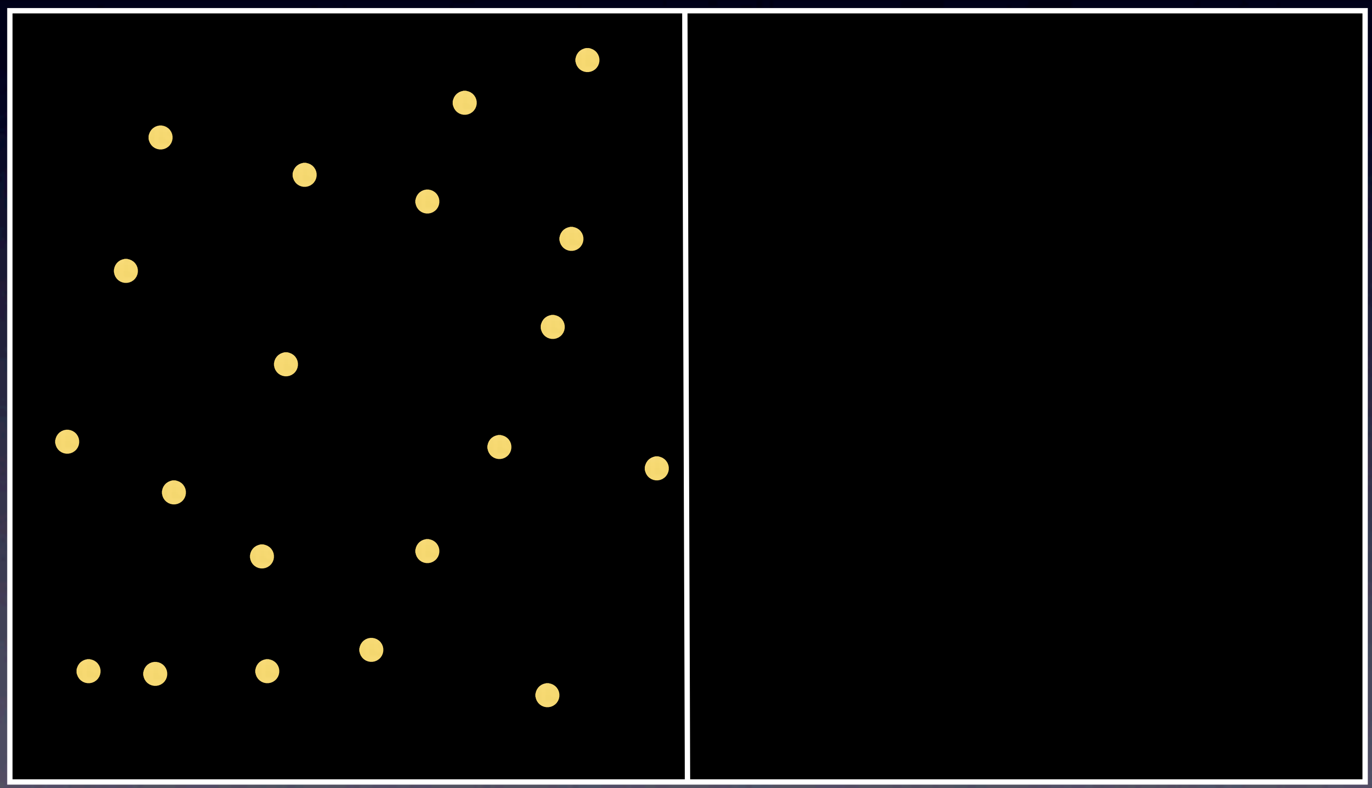
The loss is in the dispersion of the energy into the environment. The amount of dispersion of a substance is defined by the quantity entropy and is described in the 2nd Law of Thermodynamics, giving the conservation and generation of entropy

Entropy In = Entropy Out + Entropy Generation

Entropy Generation ≥ 0

Entropy is a thermodynamic variable of state used to describe operating points of thermodynamic systems, and largely influences system performance. The generation of entropy is linked to a loss in efficiency, and is always greater than zero.

Entropy



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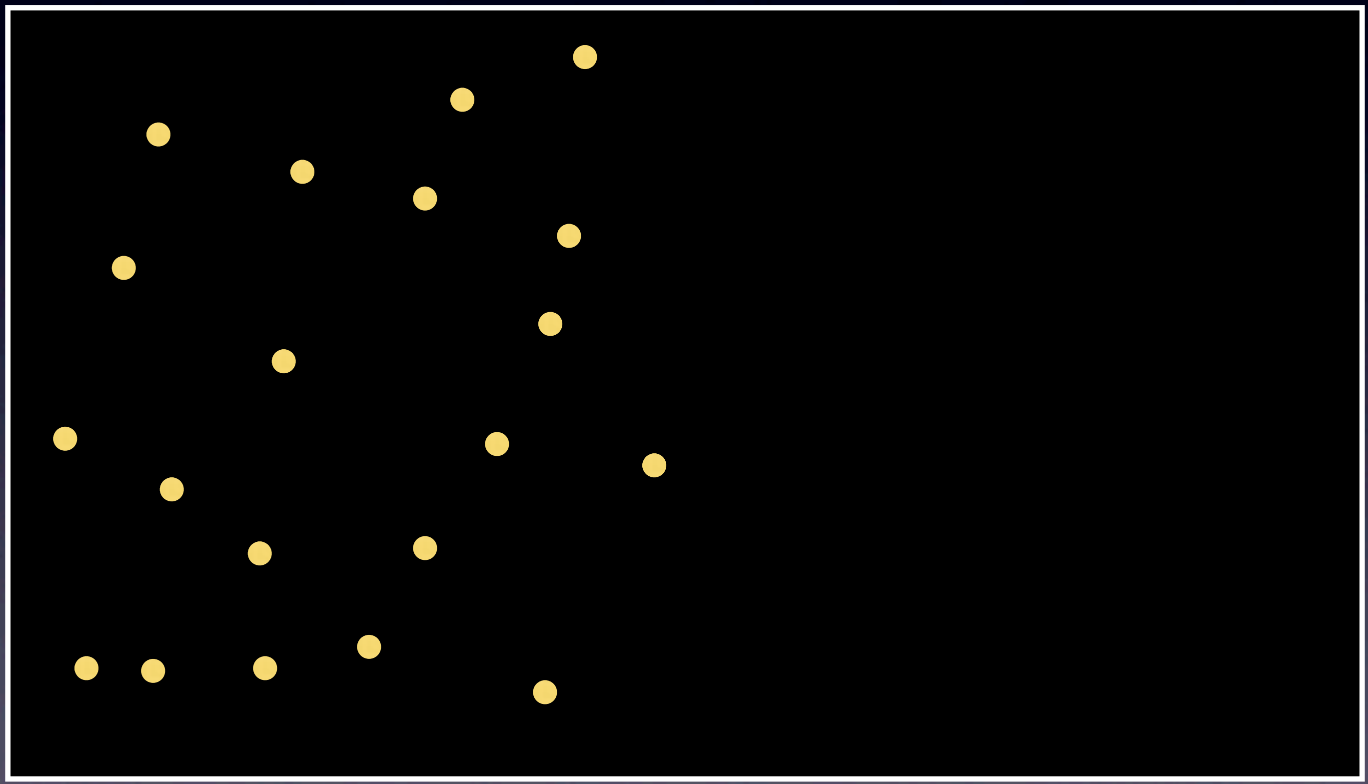

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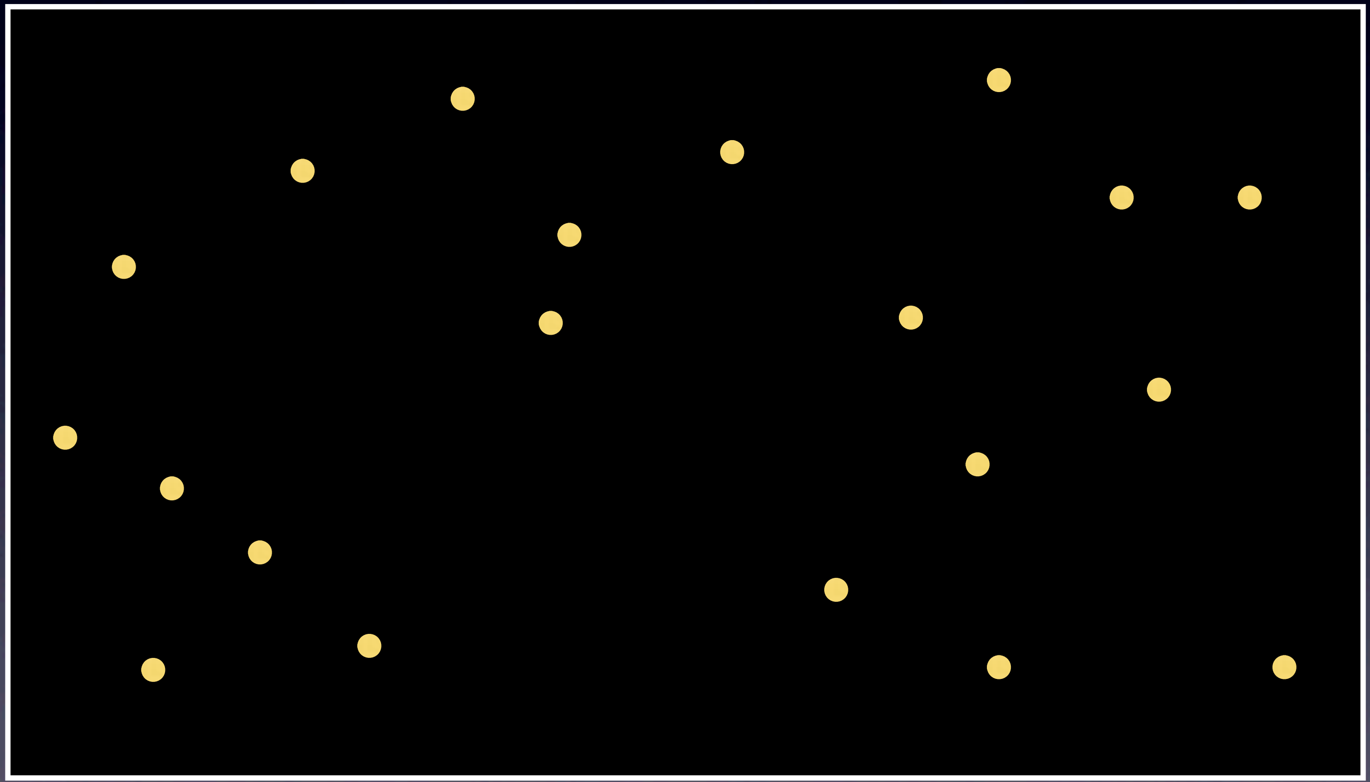

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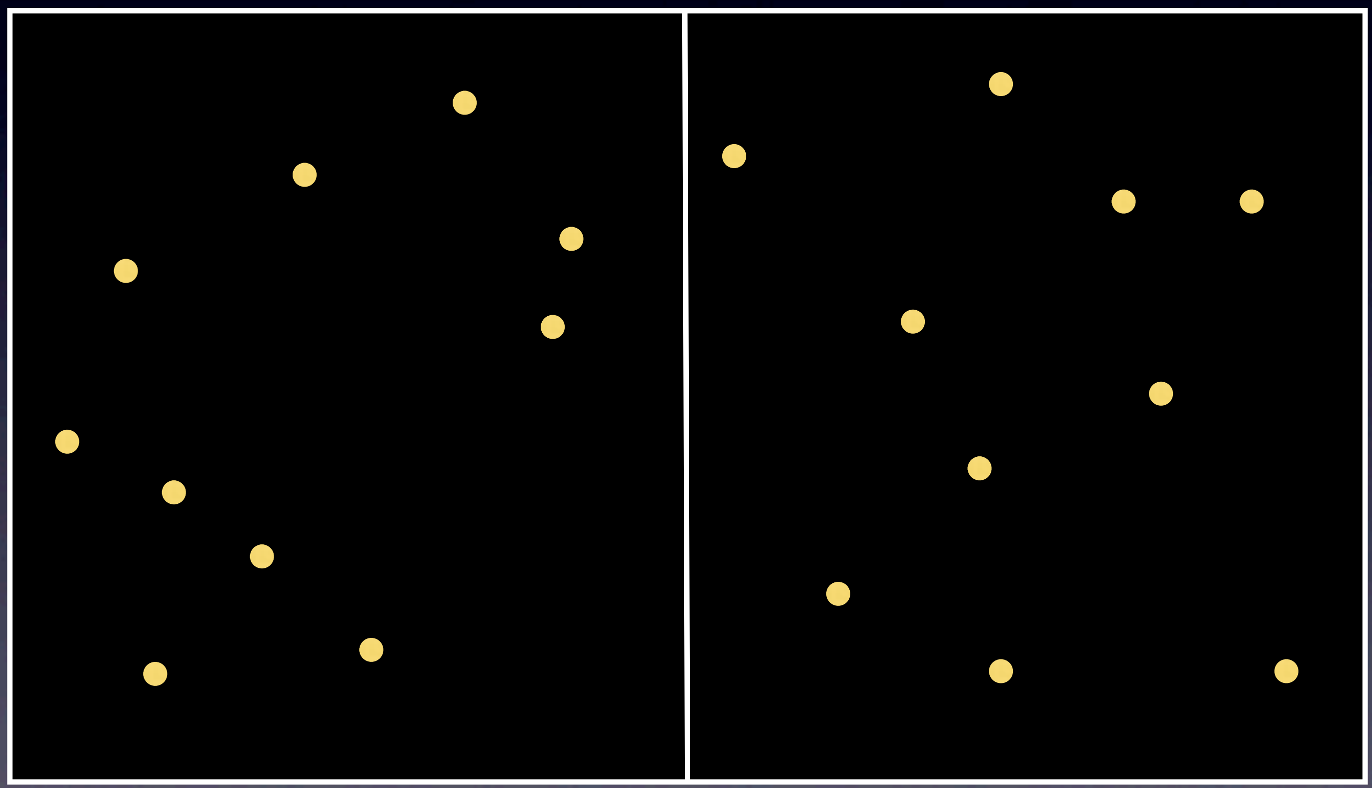
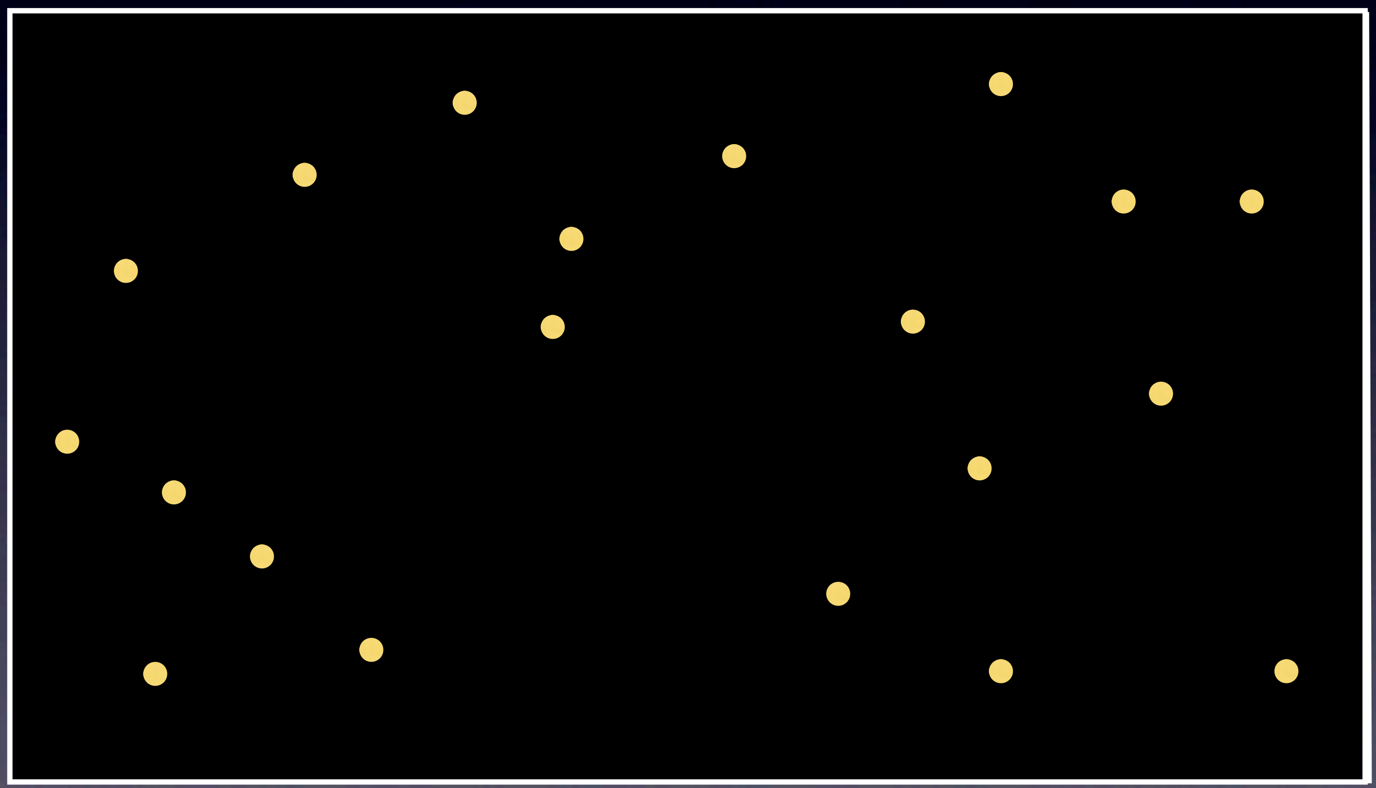
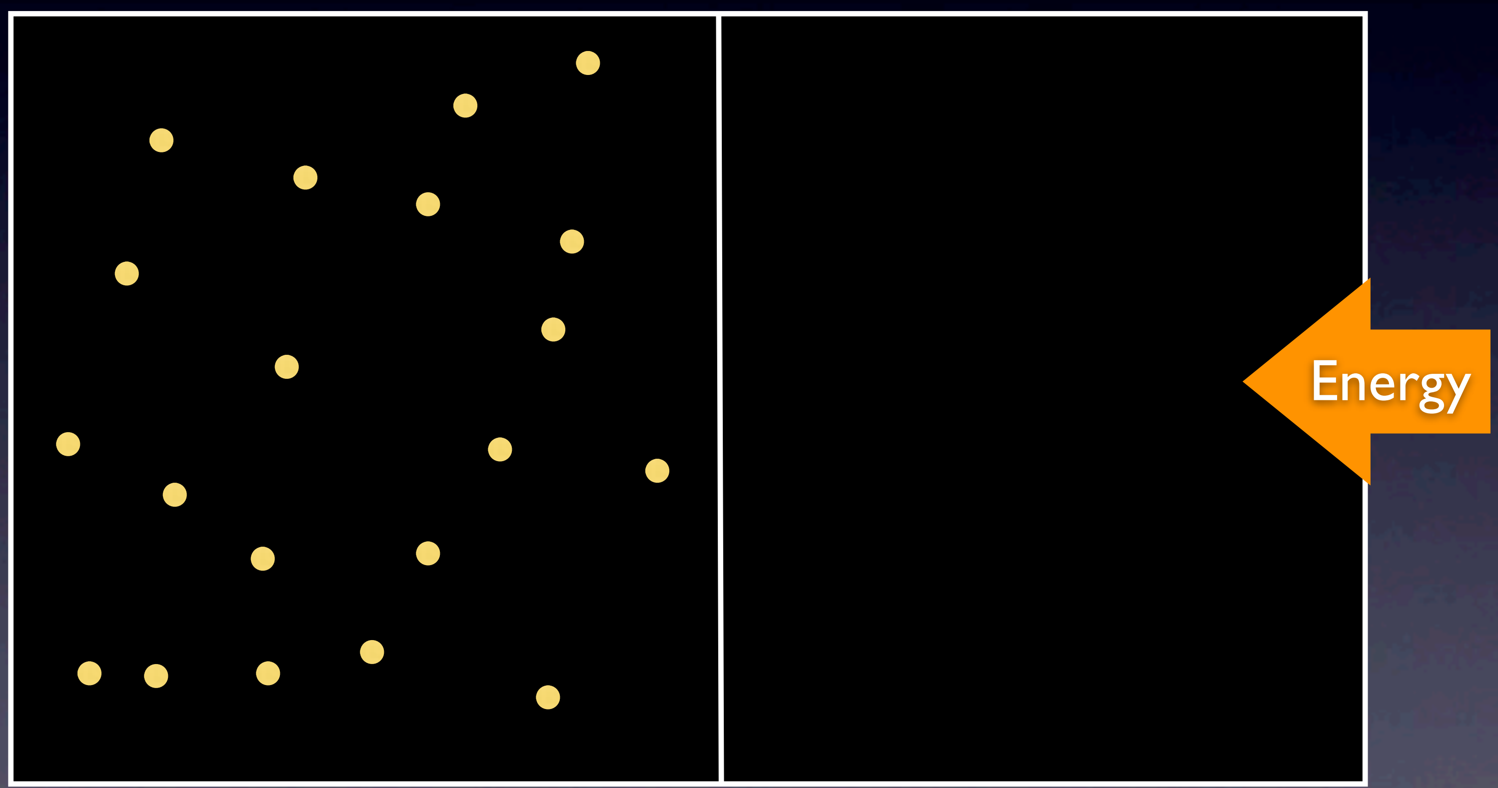


Entropy



Entropy



Exergy reveals quality

300 mL @ 40 °C
Luke warm Coffee

25 kJ Energy
800 J Exergy

@20°C
Reference
Temperature

30 mL @ 95 °C
Espresso

9 kJ Energy
1000 J Exergy

First Paradigm: Exergy

So when energy is dispersed its value is lost, and this dispersion is entropy

Also in any thermodynamic system entropy is generated, including building systems, so minimizing entropy generation helps reduce dispersion and increase performance.

It would be useful to develop a concept to consider both the amount of energy needed for a system to operate as well as its losses due to entropy generation.

This concept is Exergy:

Exergy (Ex) is a result of combining the 1st and 2nd laws of thermodynamics, namely the energy (E) and entropy (S) balances.

Exergy = Energy - (Entropy)(Temperature of Environment)
[Anergy]

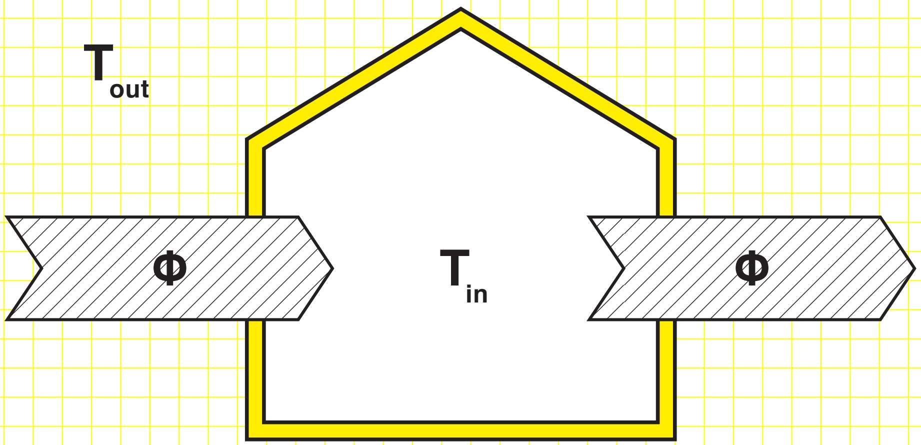
This describes the theoretical maximum work that could be done by a system when it operates using the environmental temperature as a source or sink. If the system is at equilibrium with its environment, there is no potential to do work, and the exergy is zero.

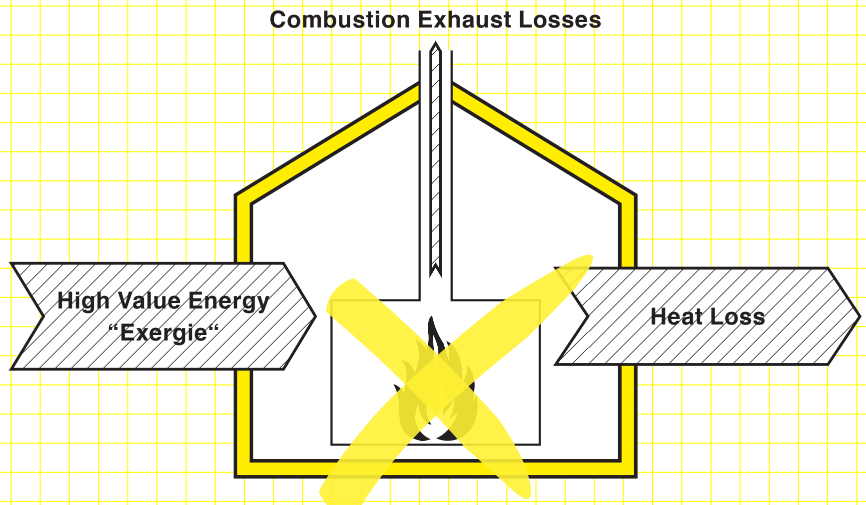
First Paradigm: Buildings and Exergy

Buildings are generally not at equilibrium with their external environment. In fact their purpose is to create a comfortable indoor environment protected from extreme cold or hot as well as humidity and weather such a wind, rain and snow.

Exergy is supplied to a building to maintain this non-equilibrium

But buildings contain a very low value energy “low exergy” volume of air so it does not make sense to use high value energy sources like combustion to heat them



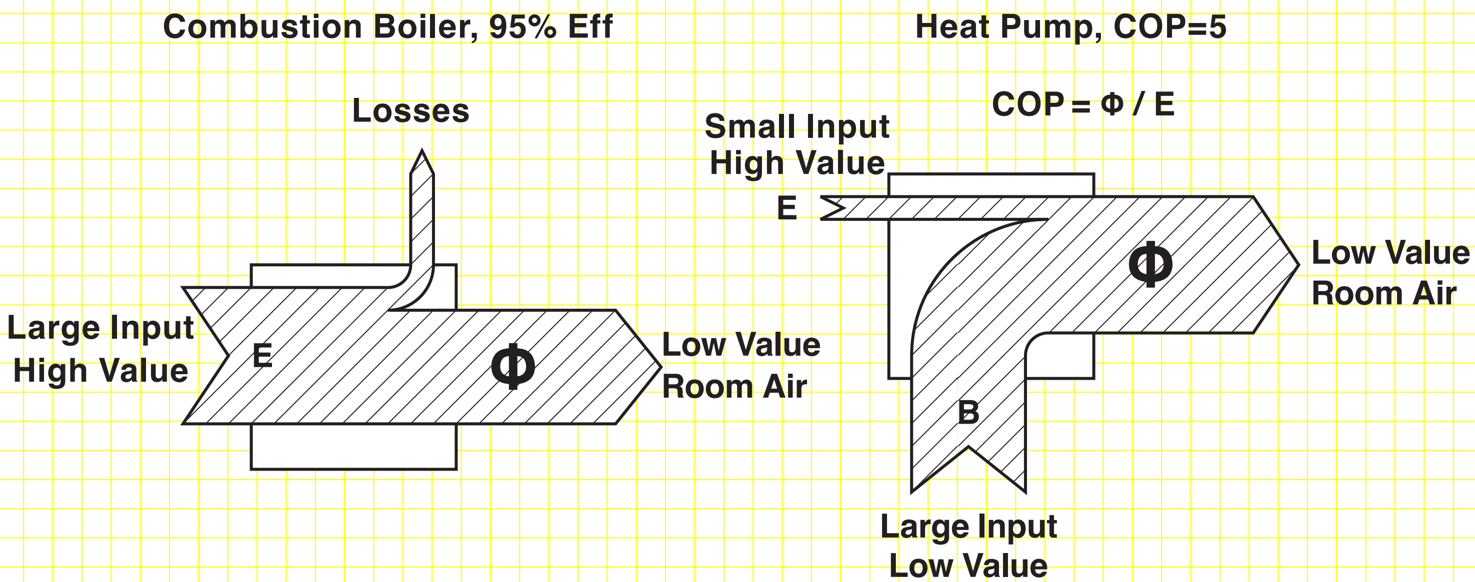


First Paradigm: Heat Pumps

Heat Pumps can extract energy from the environment at a low quality and provide a small increase in quality for use to heat buildings

The heat pump Coefficient of Performance defines the ratio of the amount heat provided with an input of exergy (electricity) and is often in the range of 3-5

- this means 3-5 units of heat are supplied with 1 unit of elecricity
- a natural gas boiler has a maximum efficiency of about 95% so COP=0.95



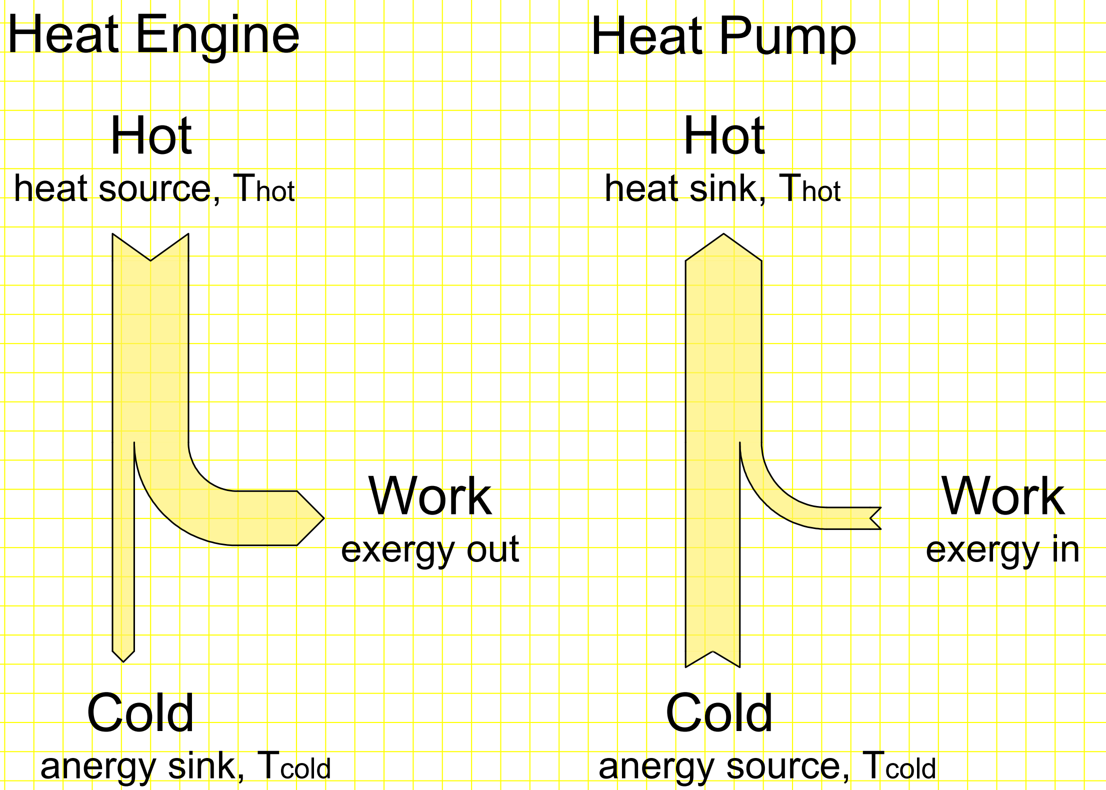
First Paradigm: A Brief Review of Heat Pumps

A heat pump is just a heat engine operating in reverse. Instead of extracting work (exergy) from the flow of heat from a hot to a cold source, work (exergy) is input to move heat in the opposite direction.

The second law limits the performance of such a system based on the temperatures

$Eff_{max} =$

$(T_H - T_C) / T_H$



$COP_{max} =$

$T_H / (T_H - T_C)$

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First Paradigm: COP and Low Temp Heating

For a heat pump performance is measured heat amount (Q) that can be supplied, divided by required electricity (W). For AC/Chiller it is the heat removed.

$$COP_{real} = Q_{out} / W_{in}$$

For an ideal "Carnot" heat pump supplying heat a temperature T_{hot} and extracting heat from temperature T_{cold} the COP is defined as a ratio of these temperatures. For AC/Chiller it is the

$$COP_{max,carnot} = T_H / (T_H - T_C) \text{ or } T_C / (T_H - T_C) \text{ for chiller}$$

Because design temperatures are usually defined for the real system, a Carnot efficiency is often used to define the COP_{real} based on these temperatures. A good heat pump has a Carnot factor (sometimes called the g-value) of about 0.5.

$$COP_{real} = g * T_H / (T_H - T_C)$$

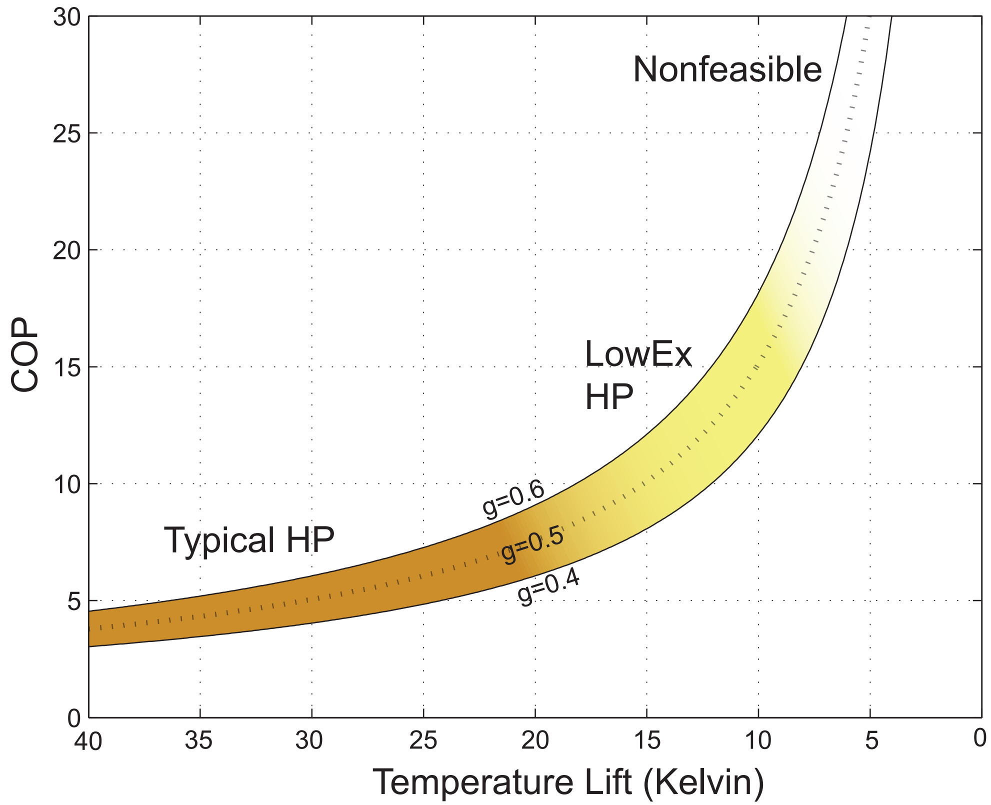
The performance is linked directly to the temperature of the heating system and to difference in the source and supply temperature, defined as the temperature lift.

First Paradigm: Heat Pump Performance

The operation of a heat pump demonstrates the value of low temperature heating

With radiator style heating at 70°C or more (343°K) there is hardly any benefit of finding a higher temperature source, but LowEx system can rapidly benefit

Heat pump with typical g-value of 0.4-0.6 gives very high potential COP



First Paradigm: Low Exergy Buildings

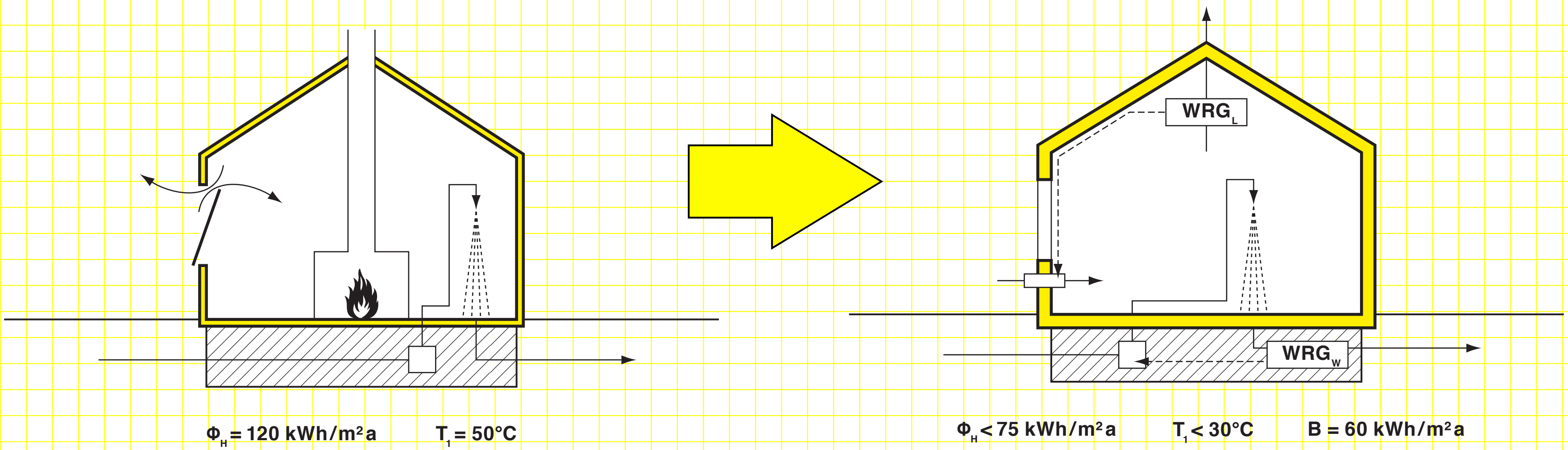
LowEx buildings account for the value of saving energy and exergy

Better insulation allows for low temperature heating or high temperature cooling using large surface areas (such as activated thermal mass in floors or ceilings)

Exergy wasting combustion sources of energy are eliminated

Exergy that would be wasted from exhaust air and wastewater can be recovered

Abundant low-value energy sources from the environment are exploited -> Paradigm 2



Second Paradigm

1) Energy is not just energy, as it also has an inherent quality: Exergy

2) There is no energy shortage, rather an energy overflow

3) Active technology is better than passive technology

Second Paradigm: Overflow

The Earth received a huge overflow of energy from the sun compared to what we use!

What we use now:
About 27,000,000,000,000 kg/a worldwide CO_2 generated through various demands
-> 8,500,000,000,000 kg/a worldwide equivalent coal energy assumed
-> 100,000,000,000,000 kWh/a of global energy demand
-> Averaged over 8760 hour/a
-> 10,000,000,000 kW very roughly needed by society

What we get everyday:
About 1kW/m^2 strikes the surface of the Earth with radius of about 6000km
-> 100,000,000,000,000 m^2 of surface on the earth
-> 100,000,000,000,000 kW supplied by the sun

Therefore the overflow of power from the sun compared to power demand is

10,000 times over!!

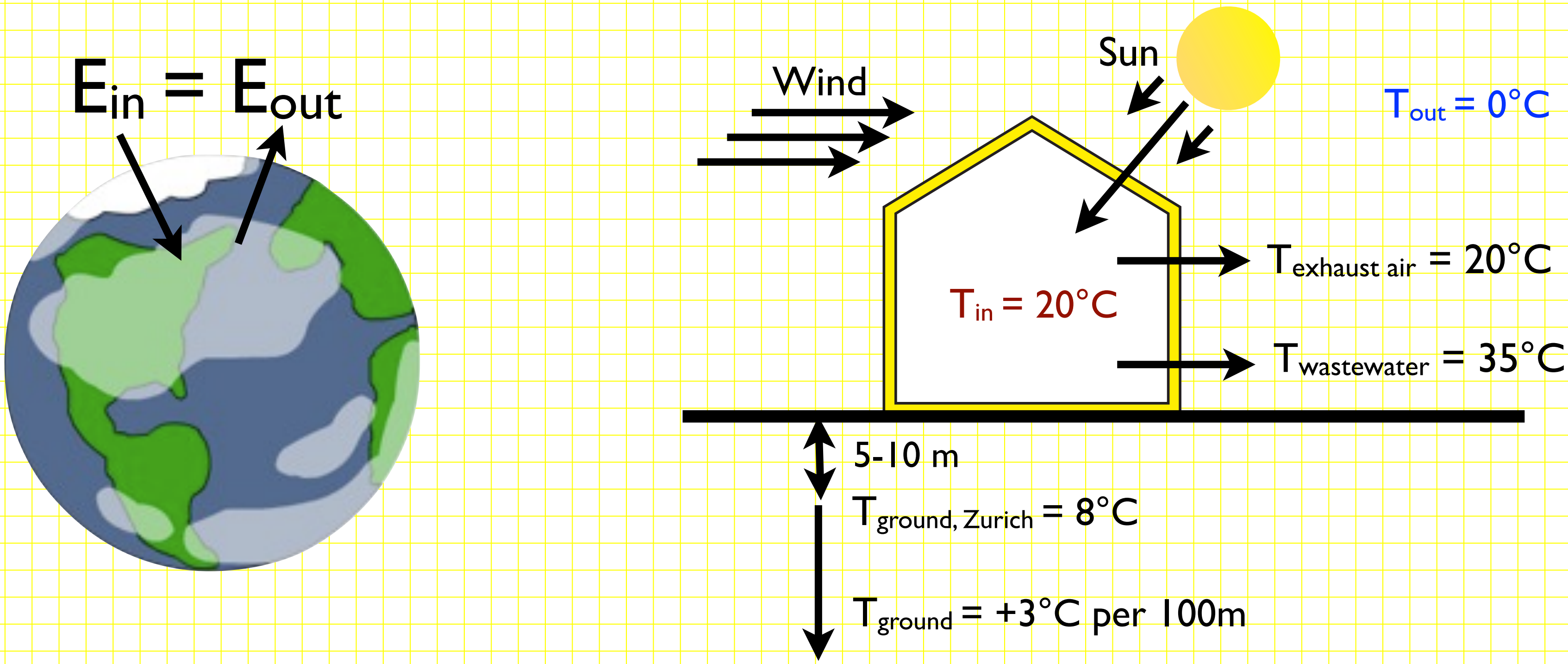
The question is only how we manage the overflow?
It is easily possible to get all that we need with 20% efficient PV... but
The present cost of PV make it important to recognize other free exergy sources

Second Paradigm: Exergy Everywhere

Exergy describes the potential to perform useful work using some source that is not at equilibrium with the environment.

By letting energy flow into the environment a part can be extracted for work

The source of the non-equilibrium can be many things:
-In fact, even though the environment is operating in equilibrium at the large scale, local non-equilibriums can be exploited as shown below



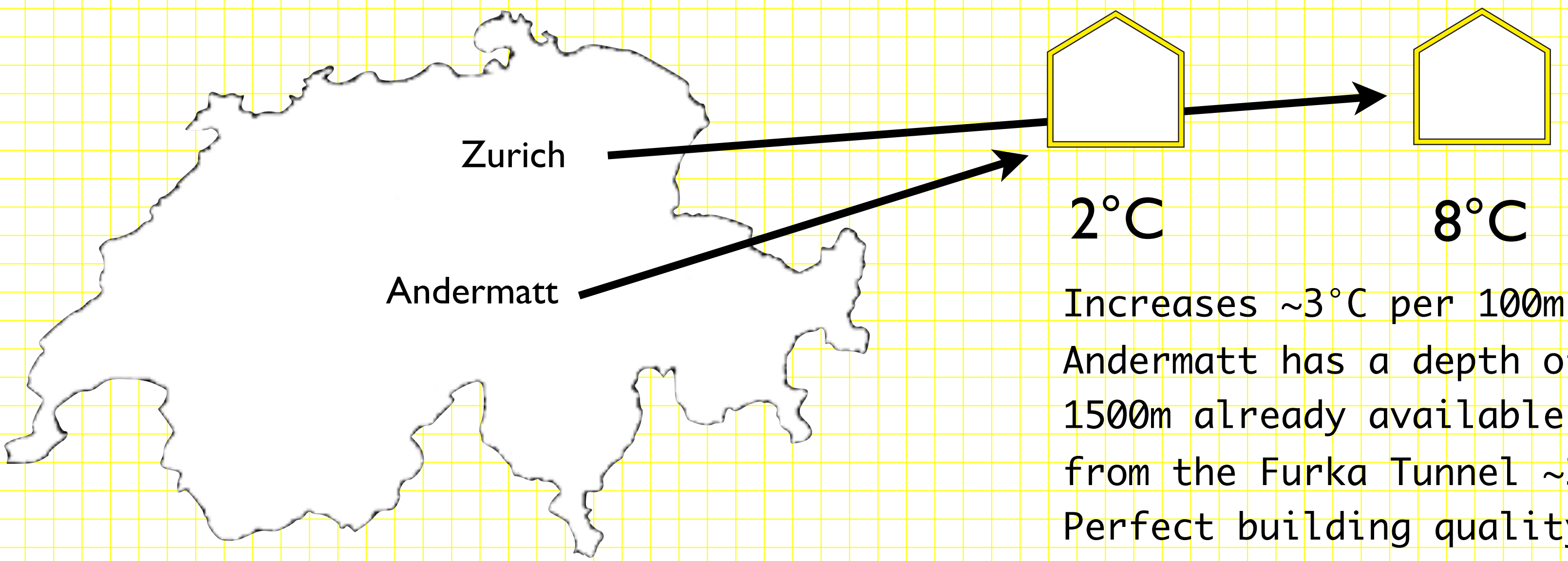
Second Paradigm: The Anergy Playground

The exergy that is or would be dispersed in the environment could be considered locally anergy.

We capture this potential by extracting the anergy for use in an exergy system.

The local environment is like an anergy playground where we find the source with the most potential when it is extracted and used in a building system

A building is a low value/low exergy system containing air at only 20°C so as stated previously, we look for matching low value sources, which are different for different places.



Increases ~3°C per 100m
Andermatt has a depth of
1500m already available
from the Furka Tunnel ~30°C
Perfect building quality

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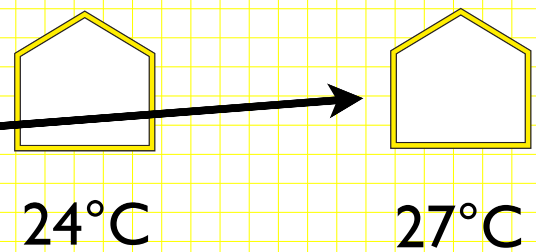
Singapore buildings also have low value, but the environmental conditions and the anergy playground is very different

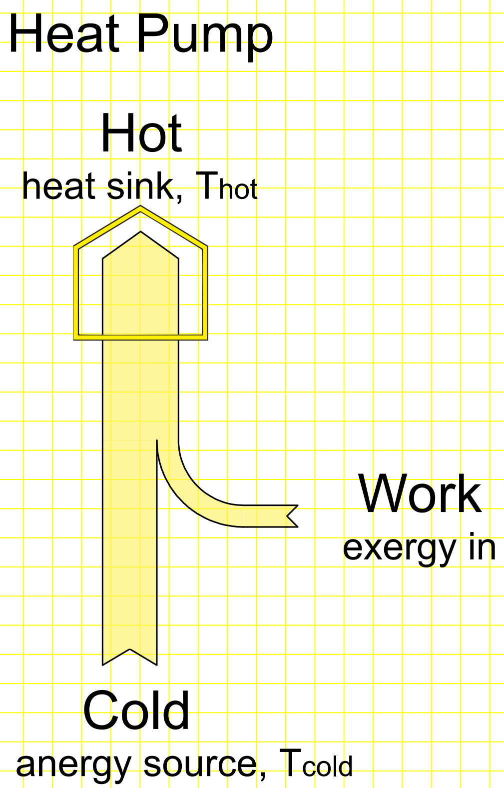


Options are not ideal. Coldest nighttime temperatures are 24°C and water temperature is 27°C

Second Paradigm: Finding Singapore's Anergy

Where on this so-called "anergy playground" can we find a relatively cool source of anergy in Singapore

Not only must we meet a cooling demand, but more important -> dehumidification



$COP_{max,HP}$ =

$T_H / (T_H - T_C)$

Design Param = T_H

and

Cold places have warm seasons

Second Paradigm: Finding Singapore's Anergy

Where on this so-called "anergy playground" can we find a relatively cool source of anergy in Singapore

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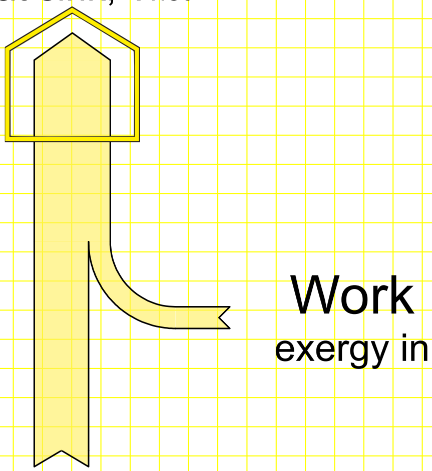
Heat Pump ➔ AC

Hot

heat sink, T_{hot}



Cold

anergy source, T_{cold}

$COP_{max,HP} = T_H / (T_H - T_C)$ ➔ $COP_{max,AC} = T_C / (T_H - T_C)$

Design Param = T_H

and

Cold places have warm seasons

Design Param = T_C

but

Warm places can lack cold seasons

Second Paradigm: Finding Singapore's Anergy

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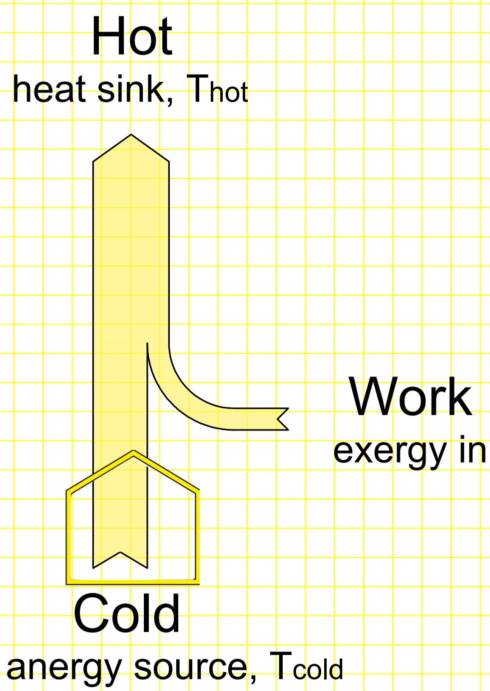
Heat Pump ➔ AC



$COP_{max,HP} = T_H / (T_H - T_C)$	→	$COP_{max,AC} = T_C / (T_H - T_C)$
Design Param = T_H		Design Param = T_C
and		but
Cold places have warm seasons		Warm places can lack cold seasons

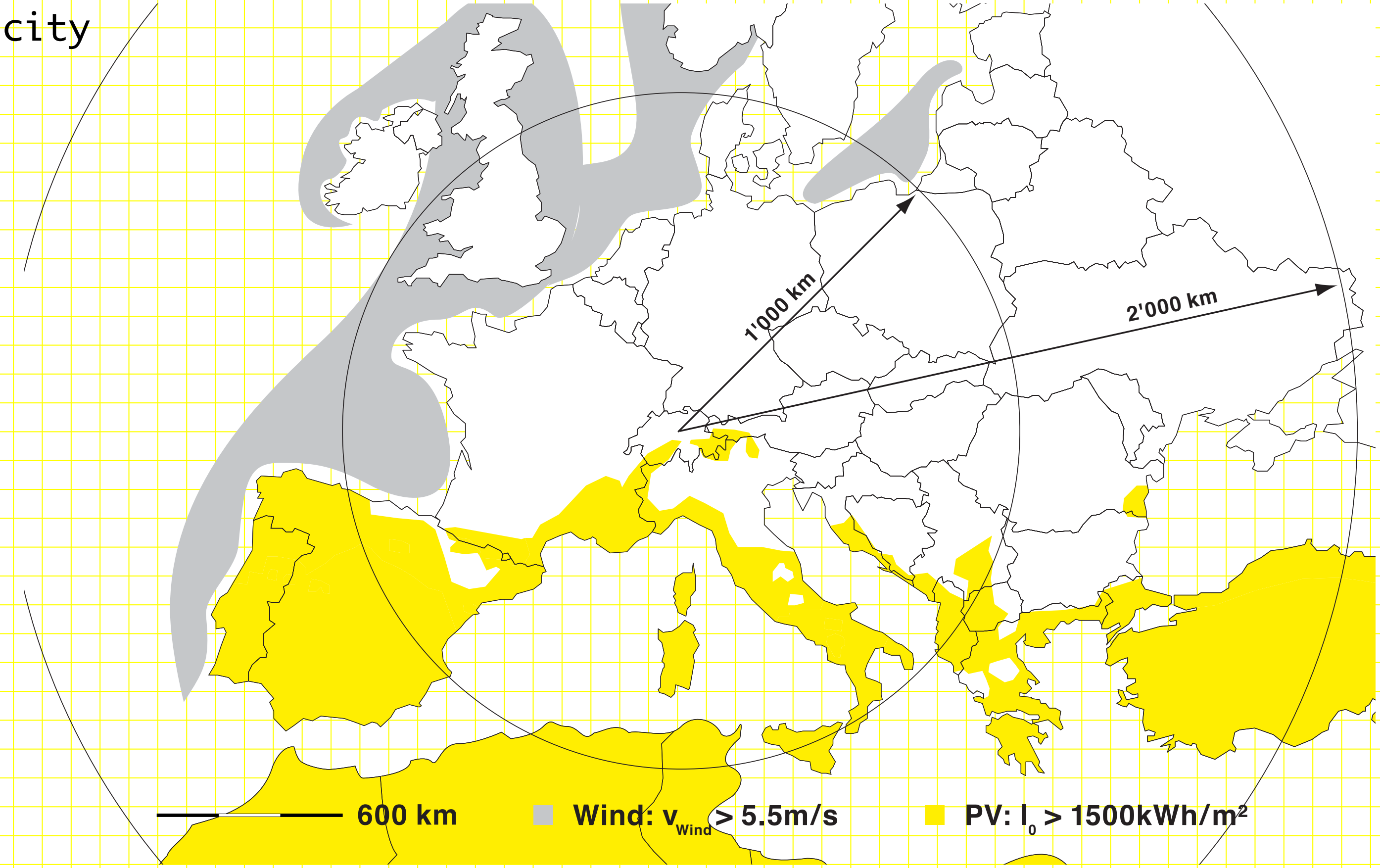
Second Paradigm: Local and Regional Overflow

The anergy sources located at a building site are not the only considerations

It also important to evaluate the regional potential sources that may pay off even if large transport is involved

In some cases electricity transport can be neglected where local fossil based production can be offset

For example in Spain electricity is still produced largely by fossil fuels so producing solar based energy as an exergy source can offset bad sources there



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Second Paradigm: Effective Overflow Capture

Now back to the house: How can the available overflow be captured

- -the house has a roof
- -could put PV or hot water collectors
- -can store the heat from the solar panel seasonally
- -the seasonal storage is integrated with the direct cooling in summer

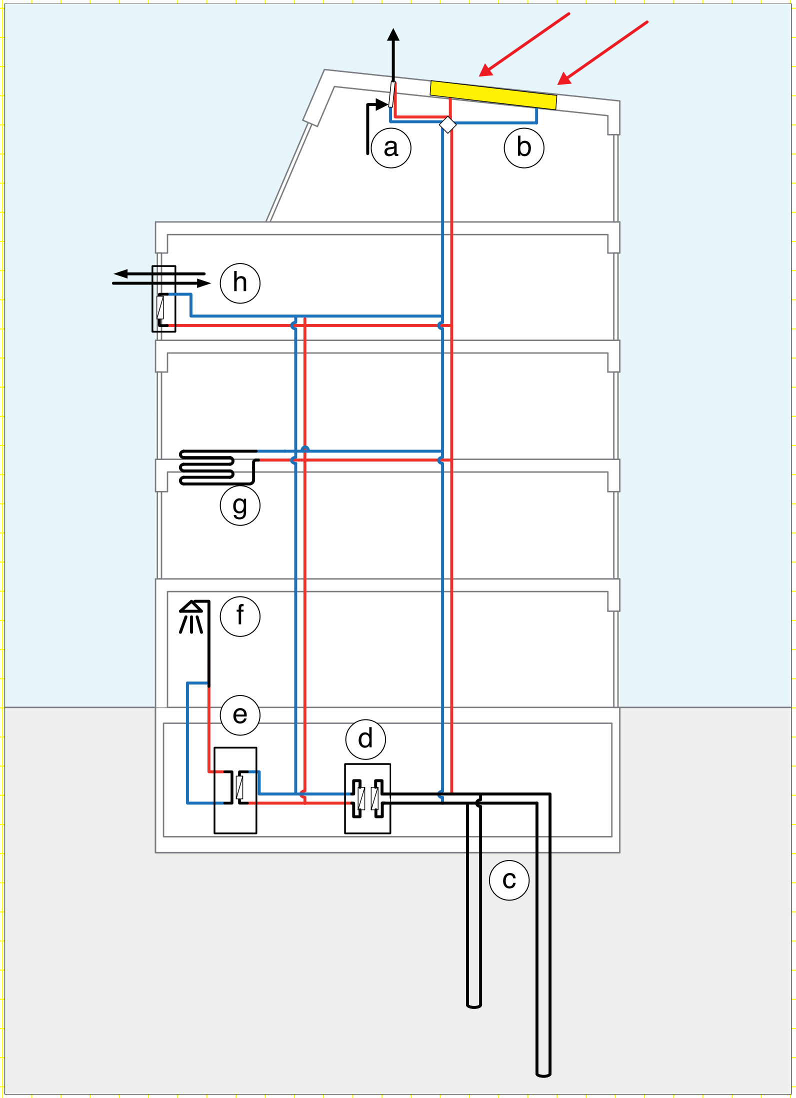
Consider the location of the house

- -What are the shading conditions (trees, other buildings, ...mountains)
- -What is the size the direction the roof faces
- -Zurich = 950kWh/m2a vs Singapore = 1600 kWh/m2a (~2x)
- -Benefits of production in higher capacity location may pays off
  - -smaller investment for with a large amount of supply

Consider the effectiveness of the technology

- -For solar hot water at ~50°C, ~70% of the solar energy can be captured
- -Heat Pump with COP>2.5 + PV at 20% is better performance
  - -COP=Heat/Elec -> Heat=PVelec*2.5 -> Heat=Elec*20%*2.5 -> Heat=Elec*50%

Second Paradigm: Introduction to Systems



(a) Exhaust heat recovery

(b) PVT hybrid panels

(c) dual zone boreholes

(d) high COP heat pump

(e) low temp hot water storage

(f) warm wastewater heat recovery

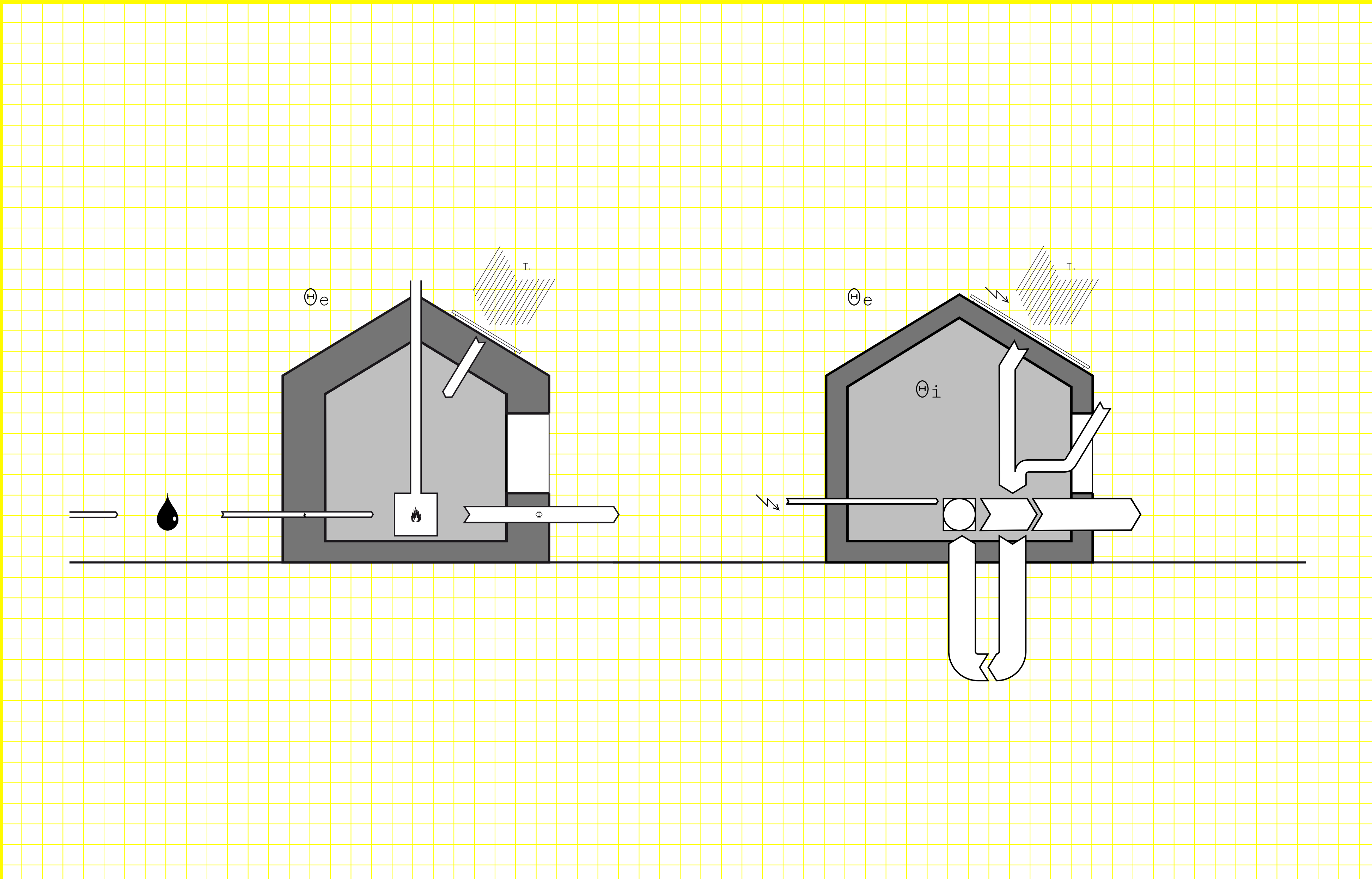
Three Paradigms

1) Energy is not just energy, as it also has an inherent quality: Exergy

2) There is no energy shortage, rather an energy overflow

3) Active technology is better than passive technology

Third Paradigm: Active versus Passive



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Third Paradigm: Building Operation

Consideration of building operation:

Typical-Swiss: Heat demand calculation, Heat supply calculation
Singapore?: Cooling and dehumidification demand, Air-based cooling sizing

LowEx: Potential heat sources, System performance potential, Demand and Supply

Third Paradigm: Extremes of Passive Standard

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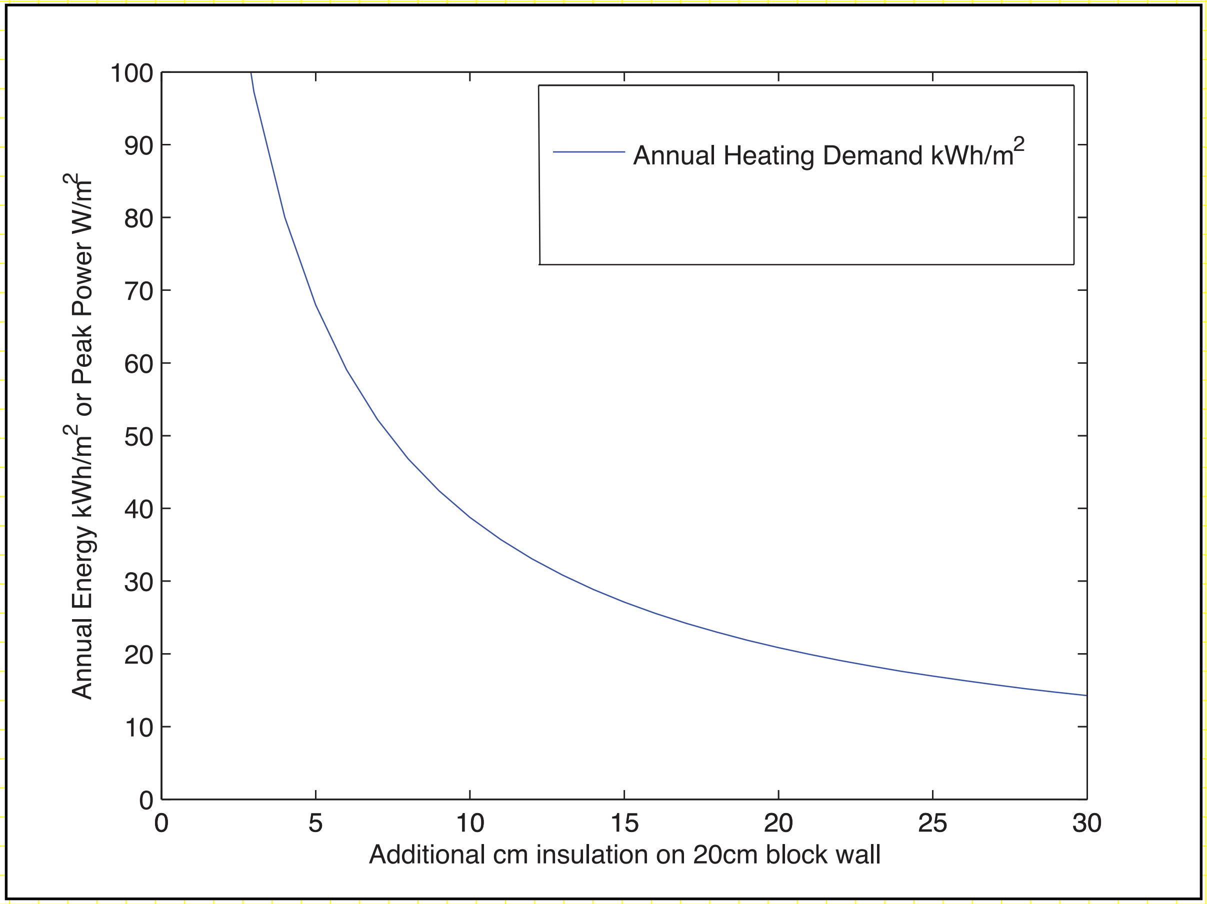

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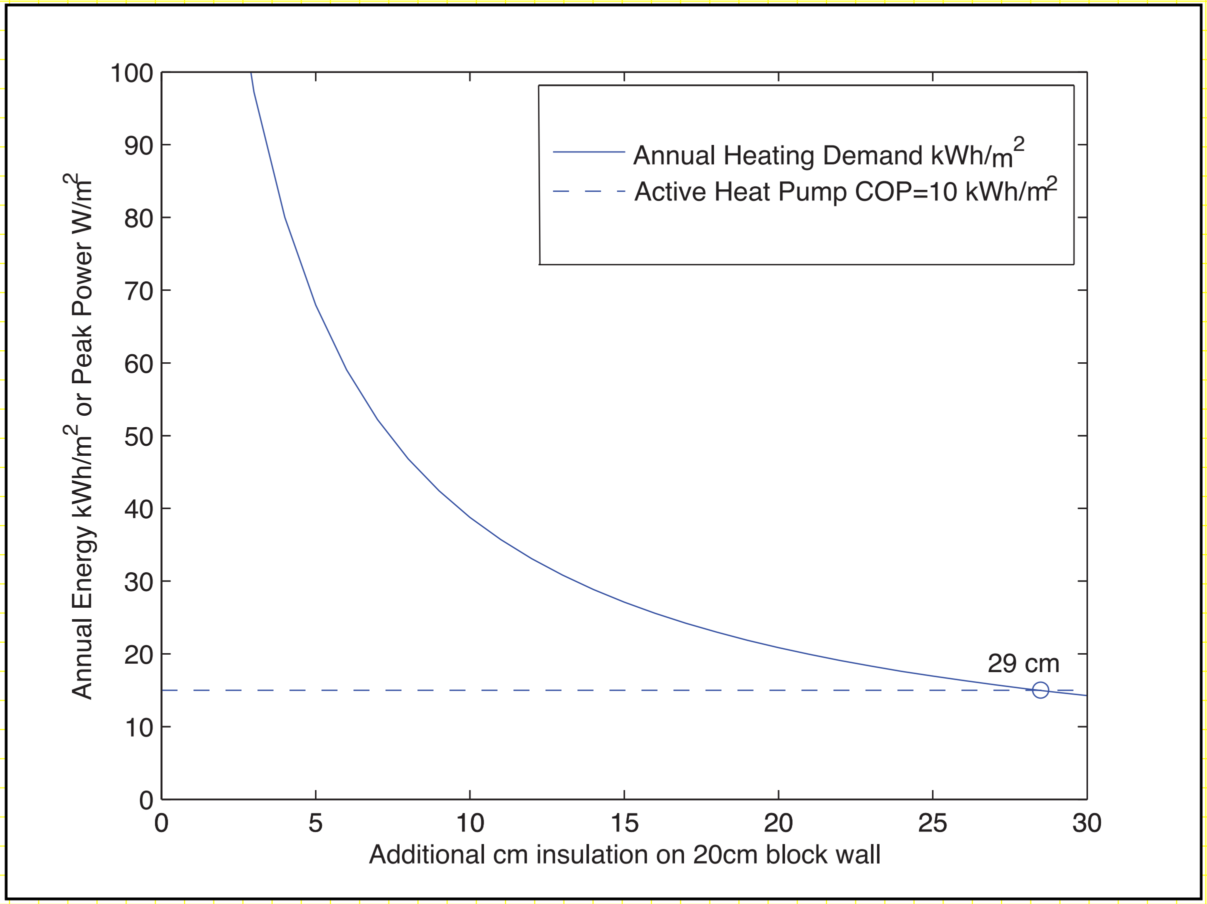

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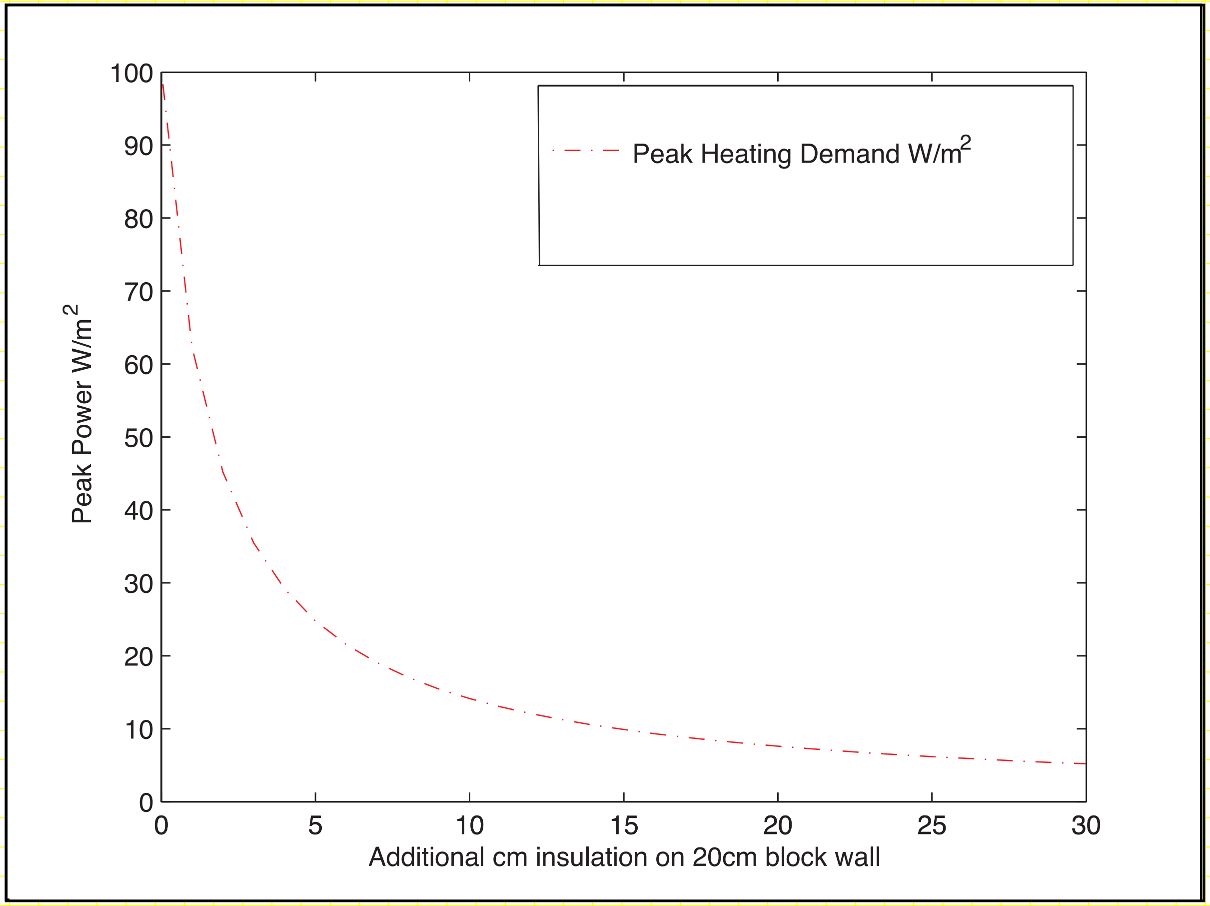

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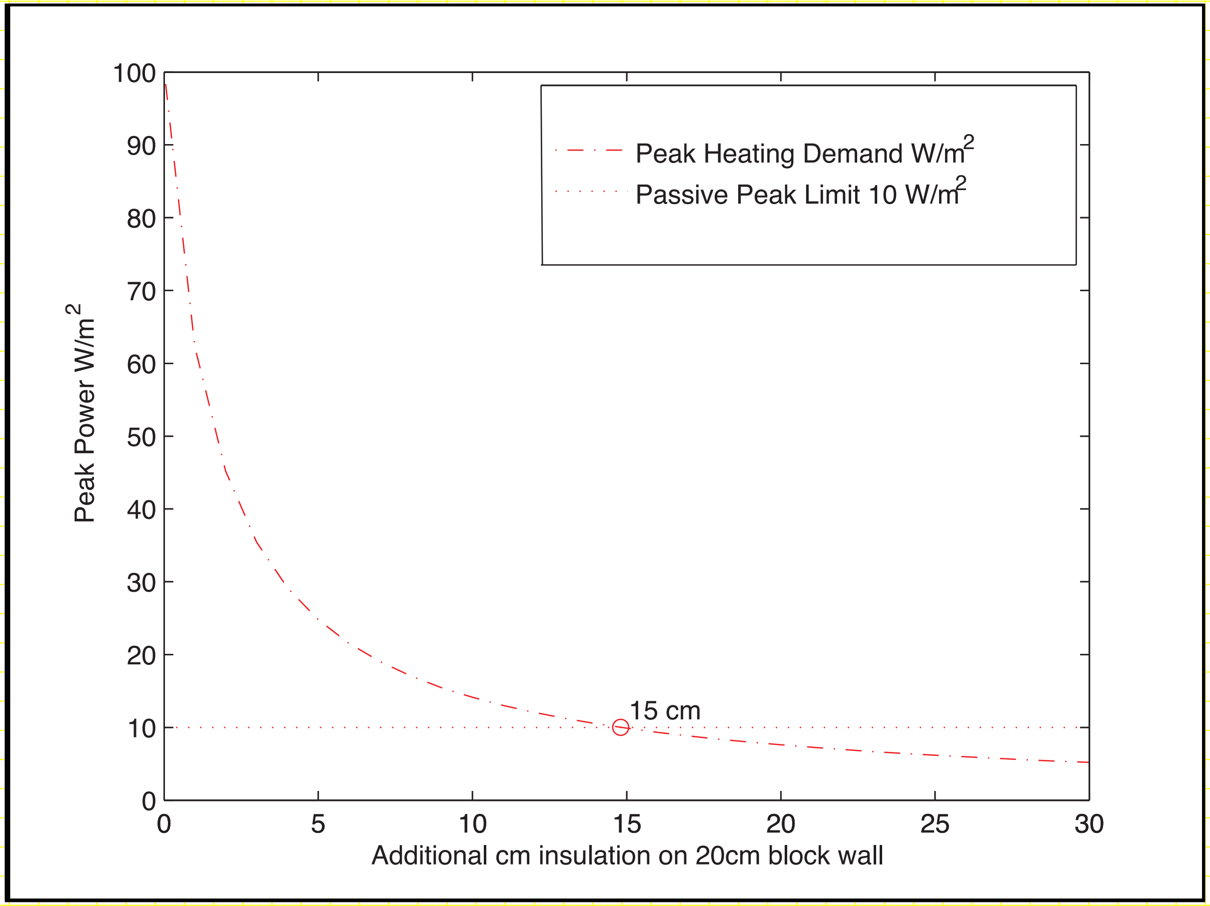

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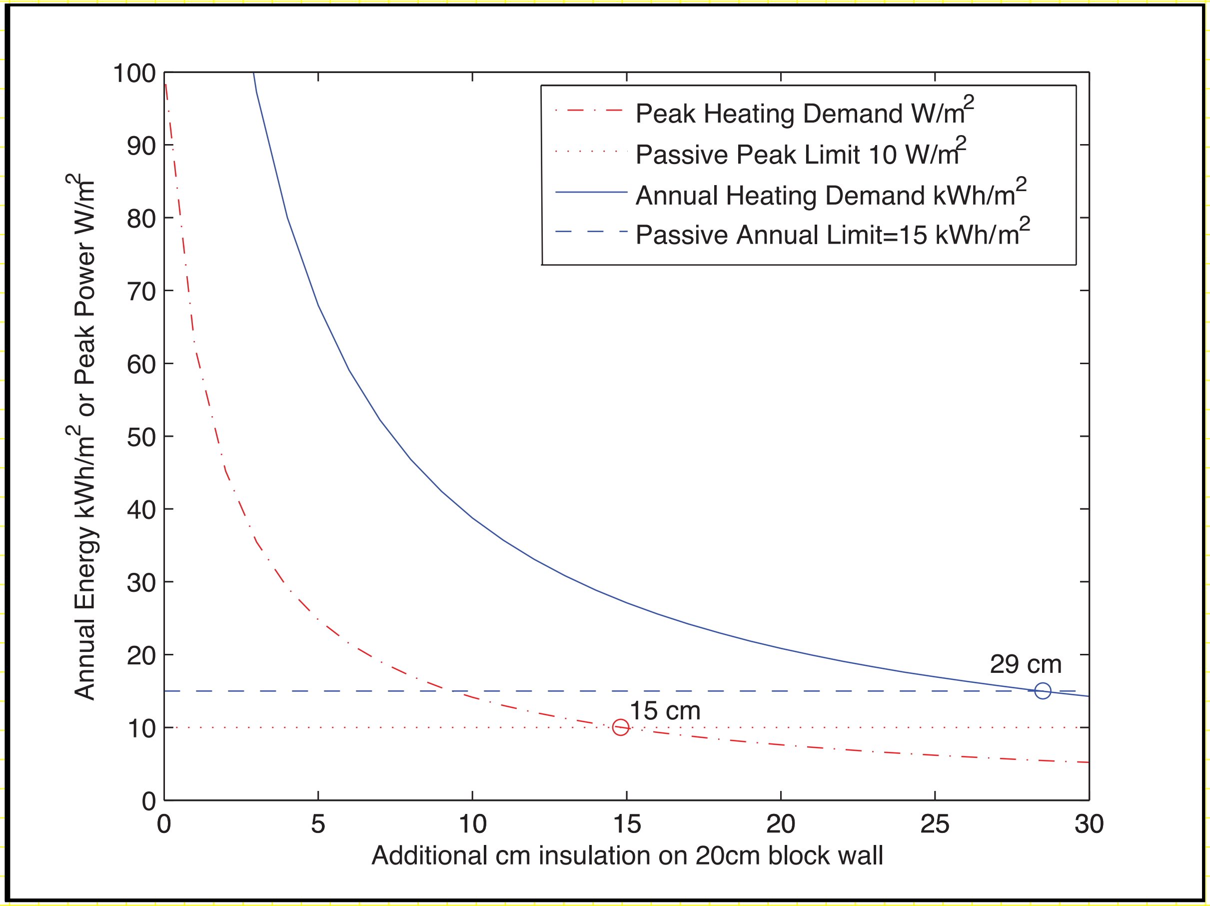

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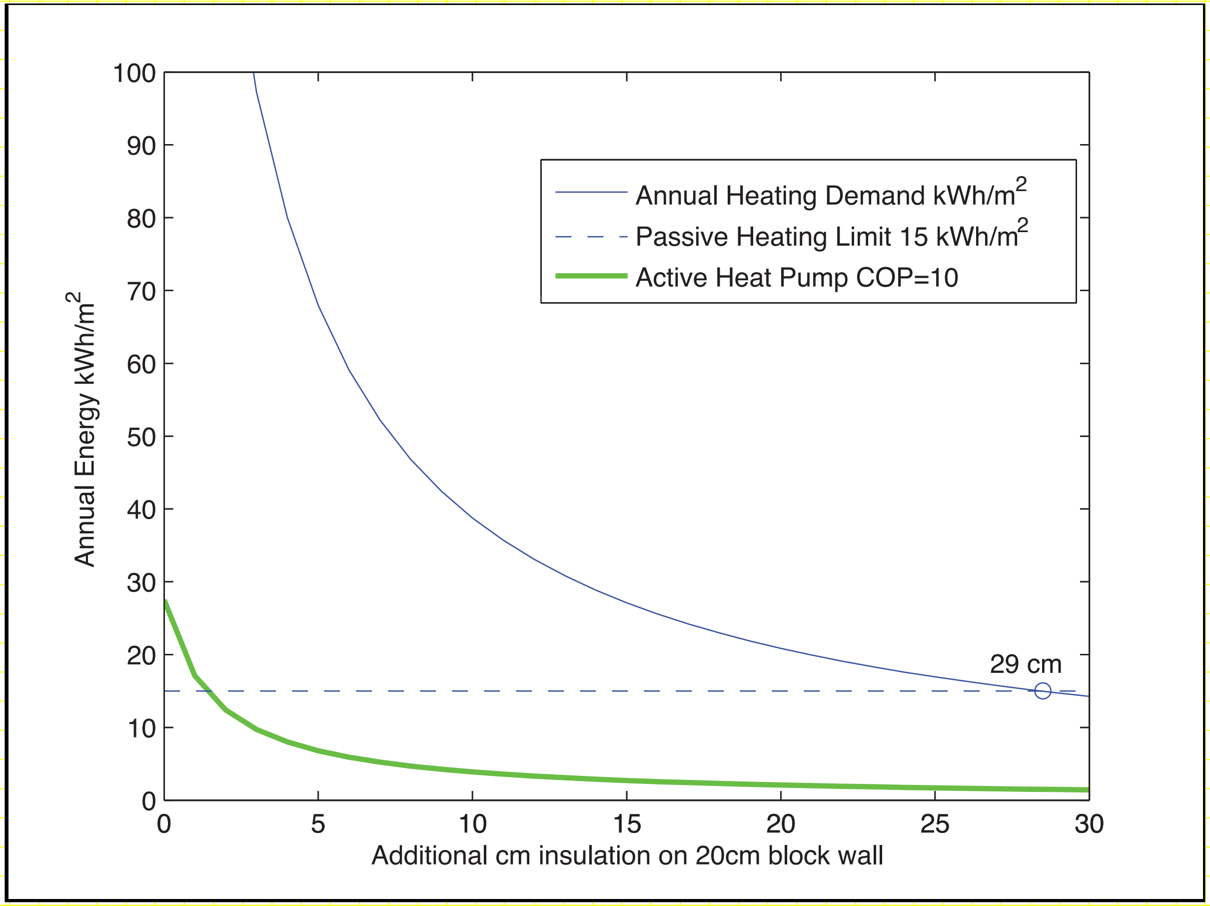

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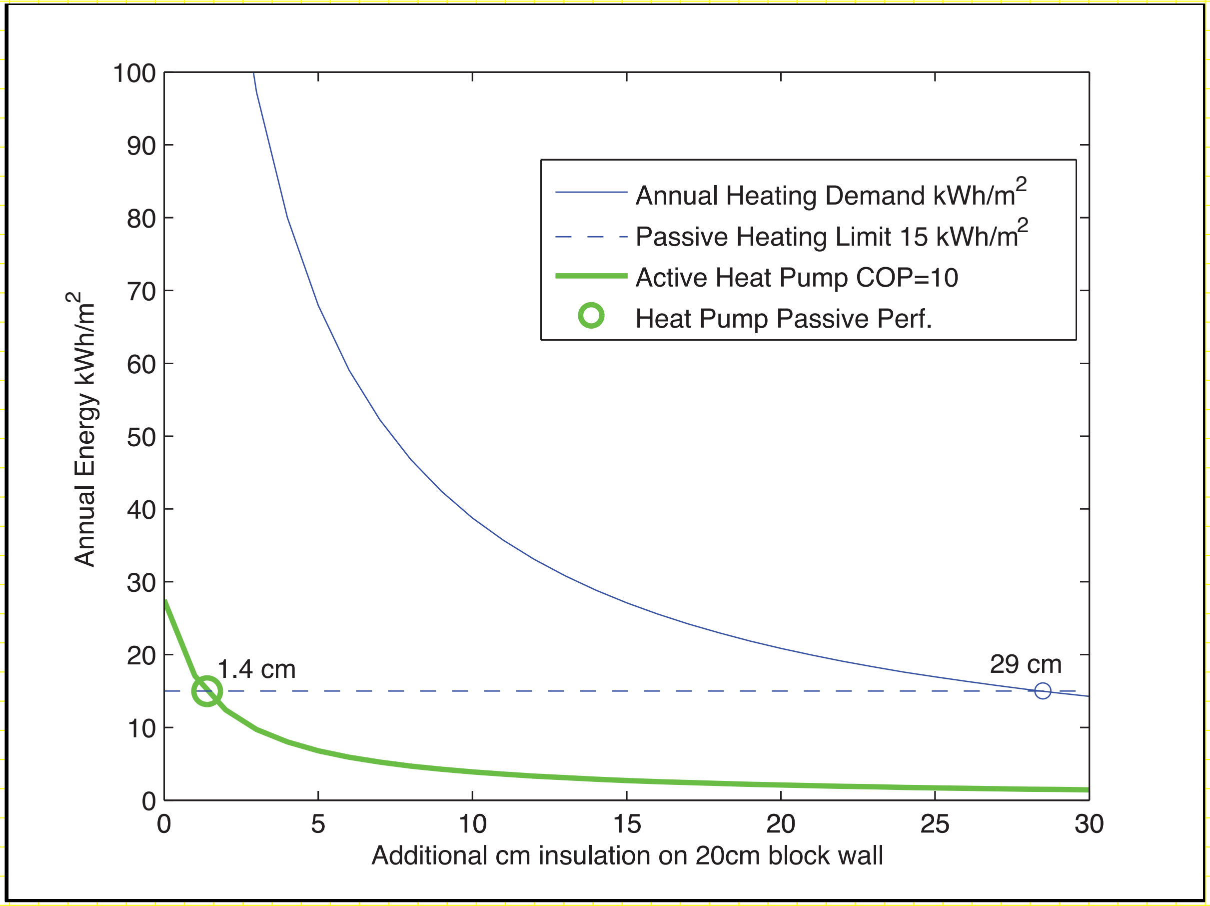

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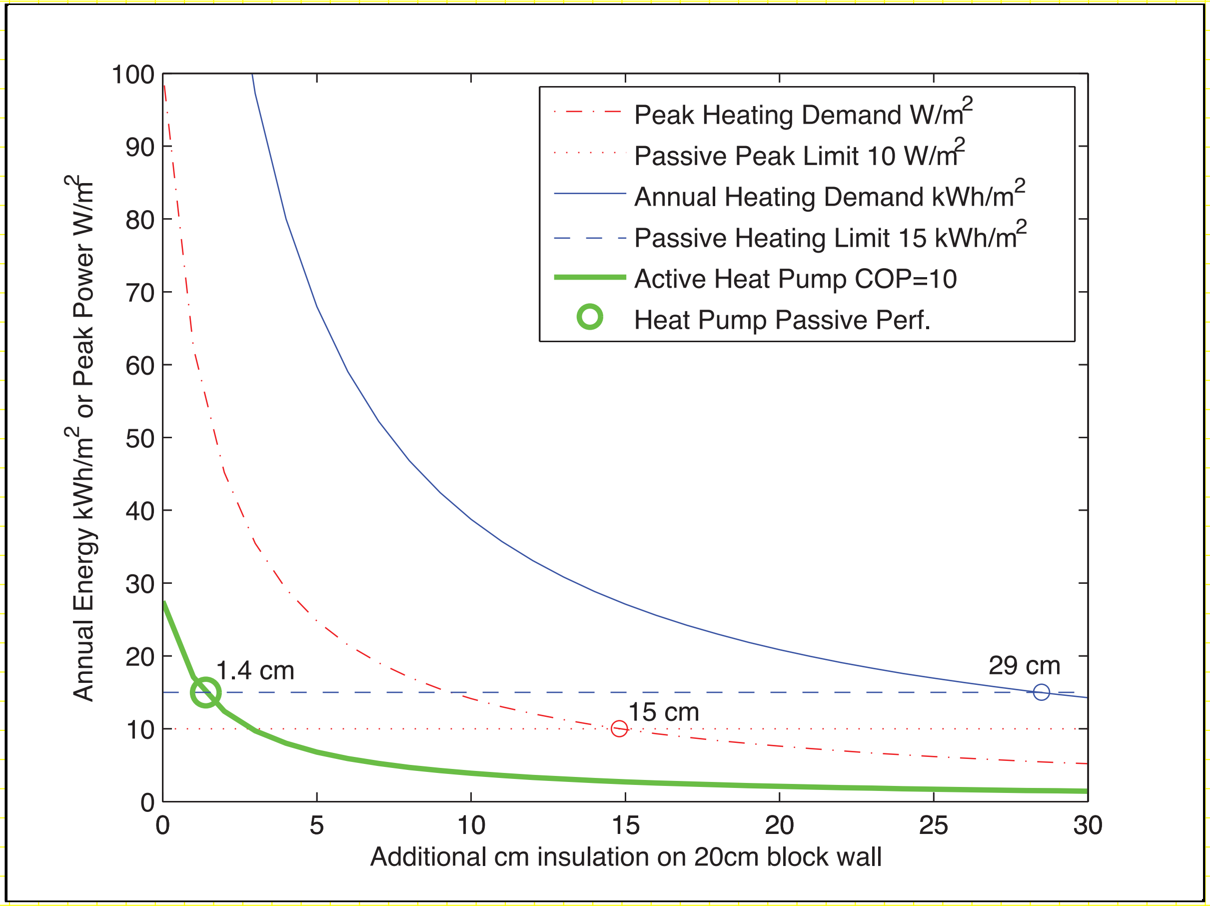

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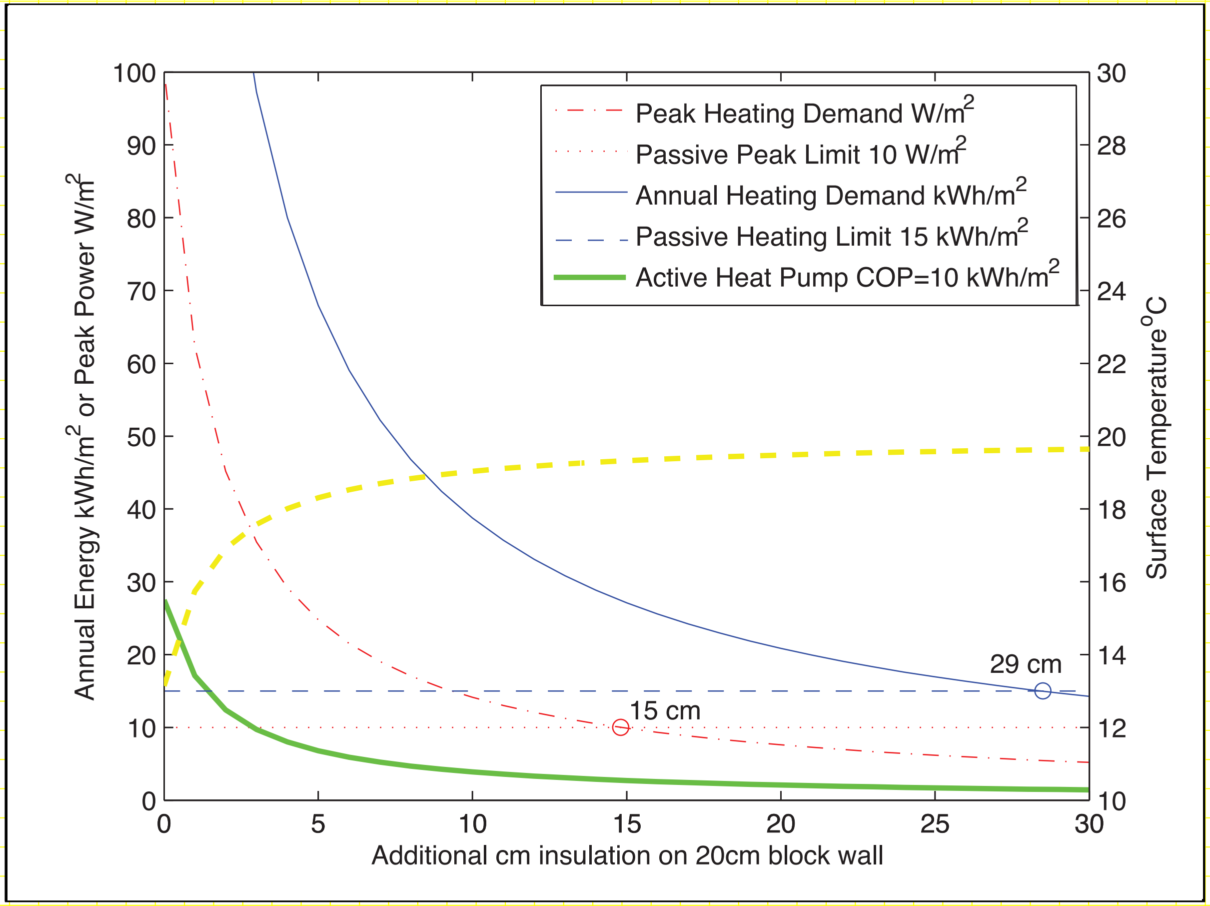

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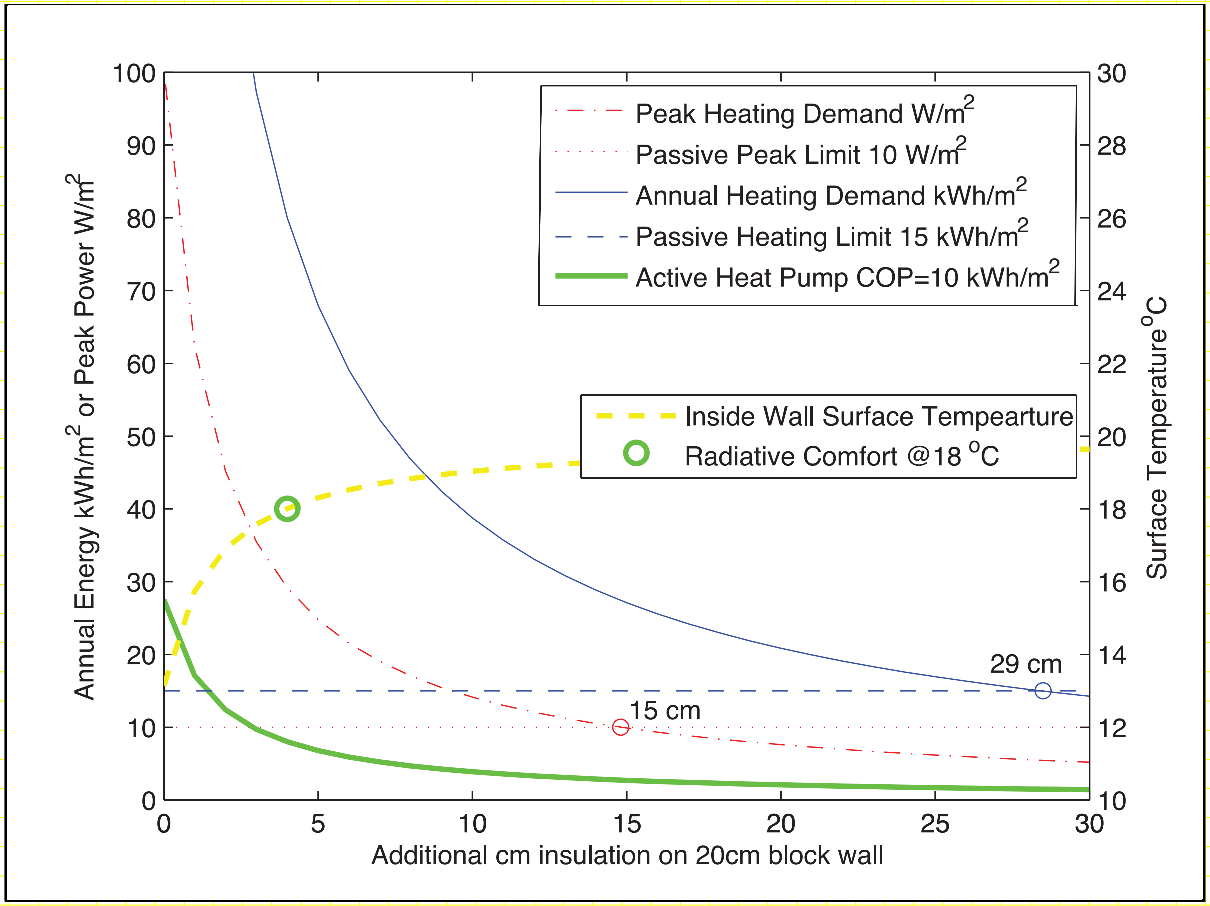
Third Paradigm: Extremes of Passive Standard



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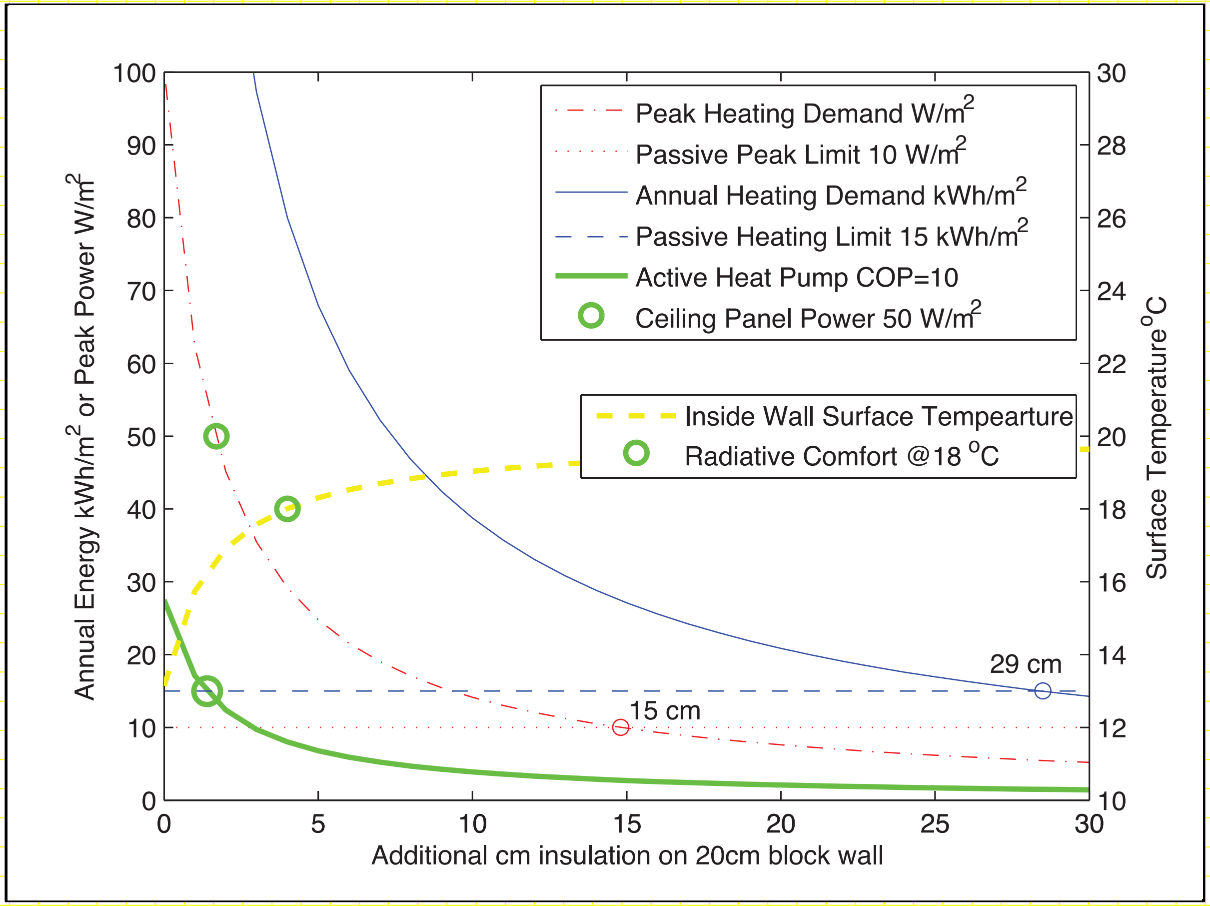

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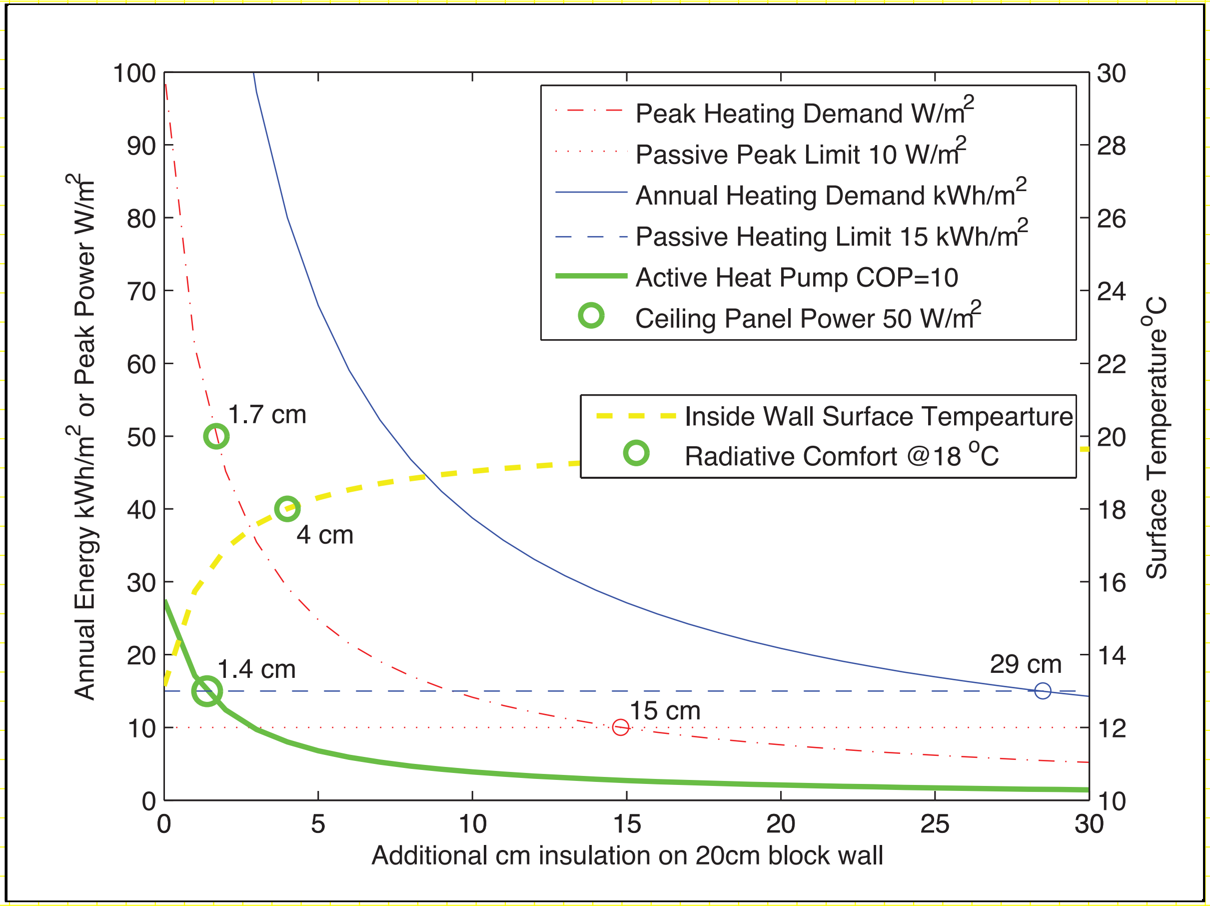

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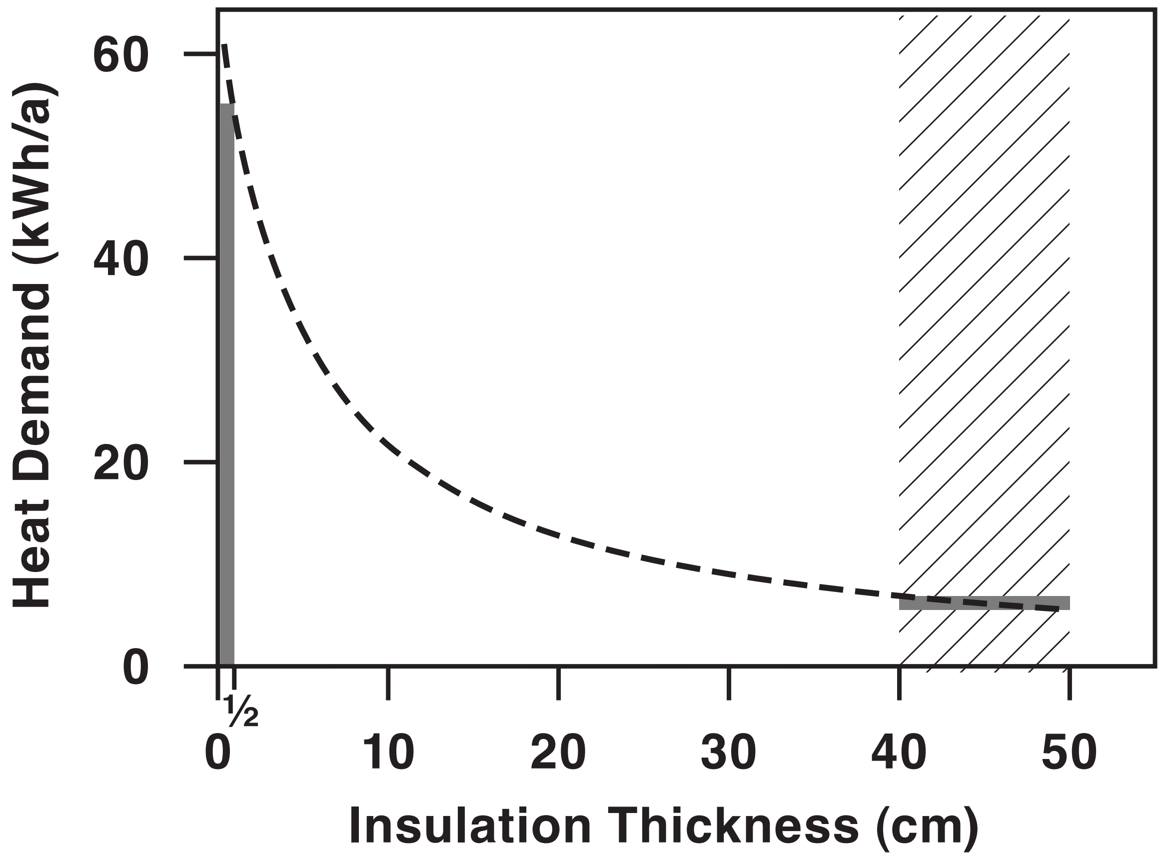
Third Paradigm: Extremes of Passive Standard

Or more simply: For a typical Passive House wall, the first 1/2 cm of insulation has the same benefit as the last 10 cm



But in Singapore what are the contributions of transmission losses?

Third Paradigm: Active House

No thick, heavy, and material intensive/expensive building shells

- -Focuses on creating a barrier to the environment
- -Not flexible in design
- -Not flexible in operation

Active systems allow for a reasonable shell design and better control

- -Maximizes use and integration with free sources from the environment
- -Increases flexibility of design
- -Increases flexibility and capabilities of operation

There are new systems that allow for more advanced control

- -Digital Chips
- -Computer Networking
- -Remote Operation
- -Predictive Control

Third Paradigm: Investing in technology

We don't want to invest in consuming energy we just want to run machines

First we want to build the machines so we have light, refrigerators, newspapers...

There are many ways they could have energy to run

-Use wood fire with a stirling engine -> chopping lots of wood (DAILY WORK!)

-everyone builds their own nuclear reactor (NO WORK!)

For solar 8 kg of Silicon can produce 1 kW of electricity

-> 2 kW in the next 10 years

When taken care of by someone in e.g. Singapore

-> 3000 kWh/a

-> enough for a building

The question remains only for us to decide what the most logical investment is

Are there potential advancements in heat pump technology applicable in Singapore

YES

Conclusion

Paradigms for the Low Exergy Concept for buildings

1) Energy is not just energy, as it also has an inherent quality: Exergy

2) There is no energy shortage, rather an energy overflow

3) Active technology is better than passive technology

How can can these be applied to the Singapore Context?