Physical and economic analysis of energy transition scenarios*
Methodology & first results

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* financial support APESE Project 2015-2017 / mission for interdisciplinarity - CNRS

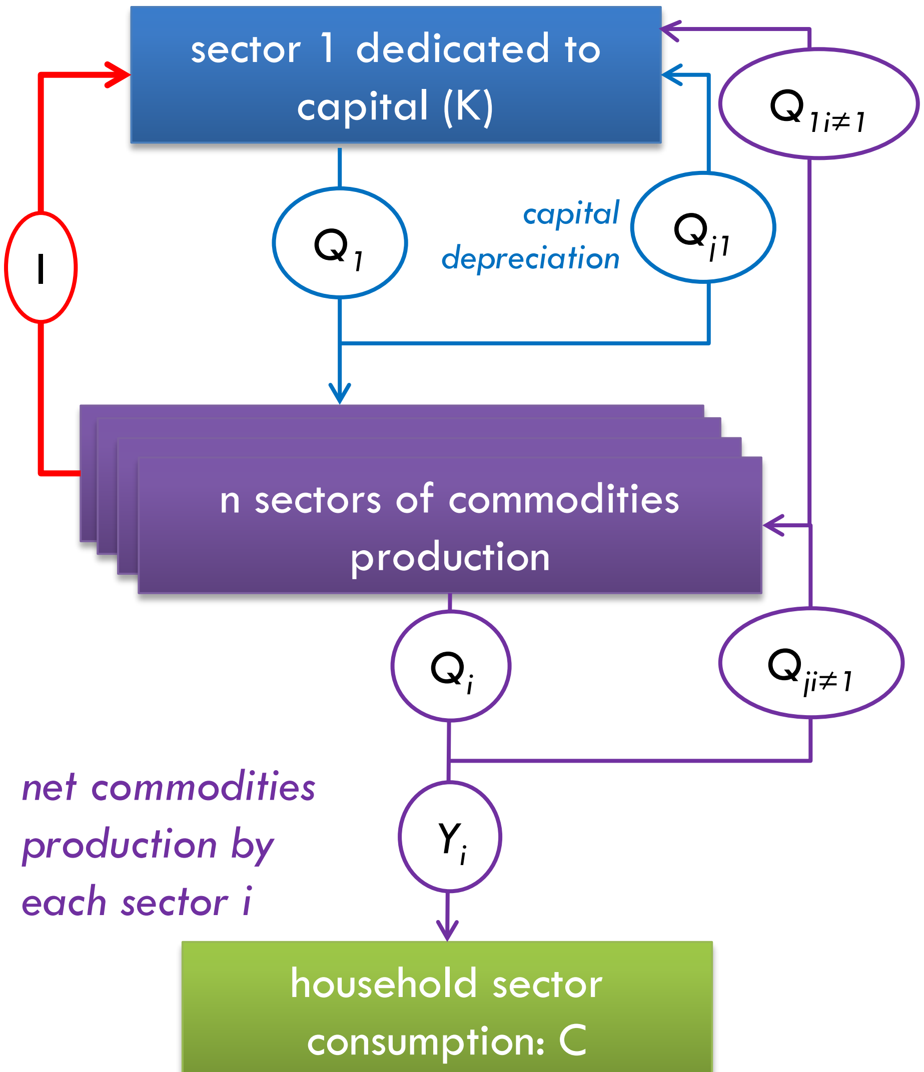
Les Houches 2018

Context & objectives

- Initial motivations
  - Evaluate the impact of an energy transition scenario on the economy
  - Elaborate a methodology and a tool able to
    - assess different scenarios within a physical approach based on a modeling of the energy production sector
    - integrate the energy sector in a complete modeling of the economic production sector to analyse their interactions

- First phase
  - Common framework, economic and physical, to build a global innovative model using the same quantities to describe two production sectors, economy and energy, deeply different but strongly correlated
  - Start first by a physical analysis of an energy transition scenario to study its correlations with economy (and not the opposite)

- Dynamic multisector economic model coupled to an « input/output » Leontief formalism



- Q_1: gross capital production used by the n sectors that produce commodities to
  - ✓ compensate the capital damages (Q_{j1})
  - ✓ construct new installations to increase the commodities production (I)
- Q_i: gross commodities production consumed by
  - ✓ the n sectors for their production ($Q_{ji\neq 1}$)
  - ✓ the sector 1 for the capital production ($Q_{1i\neq 1}$)
  - ✓ household (C)
- I: total investiment distributed among the n sectors according their profits and requires to
  - ✓ compensate the capital depreciation and damages (δK_i)
  - ✓ increase the capital $(\dot{K}_i)$

$$\begin{cases} I = \sum_{i=1}^{n} I_i \\ I_i = \dot{K}_i + \delta K_i \end{cases}$$

Model basis

- Main economic quantities to describe the dynamic of the production sector
  - Gross production of each sector i: $Q_i = \frac{K_i}{\nu_i}$
    - K_i: capital
    - ν_i: capital productivity
  - ➡ Installations run at full capacity
  - Total investment: $I(t) = \sum_i \left(\dot{K}_i + \delta K_i\right) = Q_1(t) = \frac{K_1}{\nu_1}$
    - δK_i: capital depreciation including damages
  - Net total production: $GDP = Y_1 + \sum_{i=2}^{n} Y_i = I + C$
    - $Y_1 = I$: total net capital equal to total investment
    - $\sum_{i=2}^{n} Y_i = \sum_{i=2}^{n} \left(Q_i - Q_{ji}\right) = C$: total net production of commodities and consumed by household sector

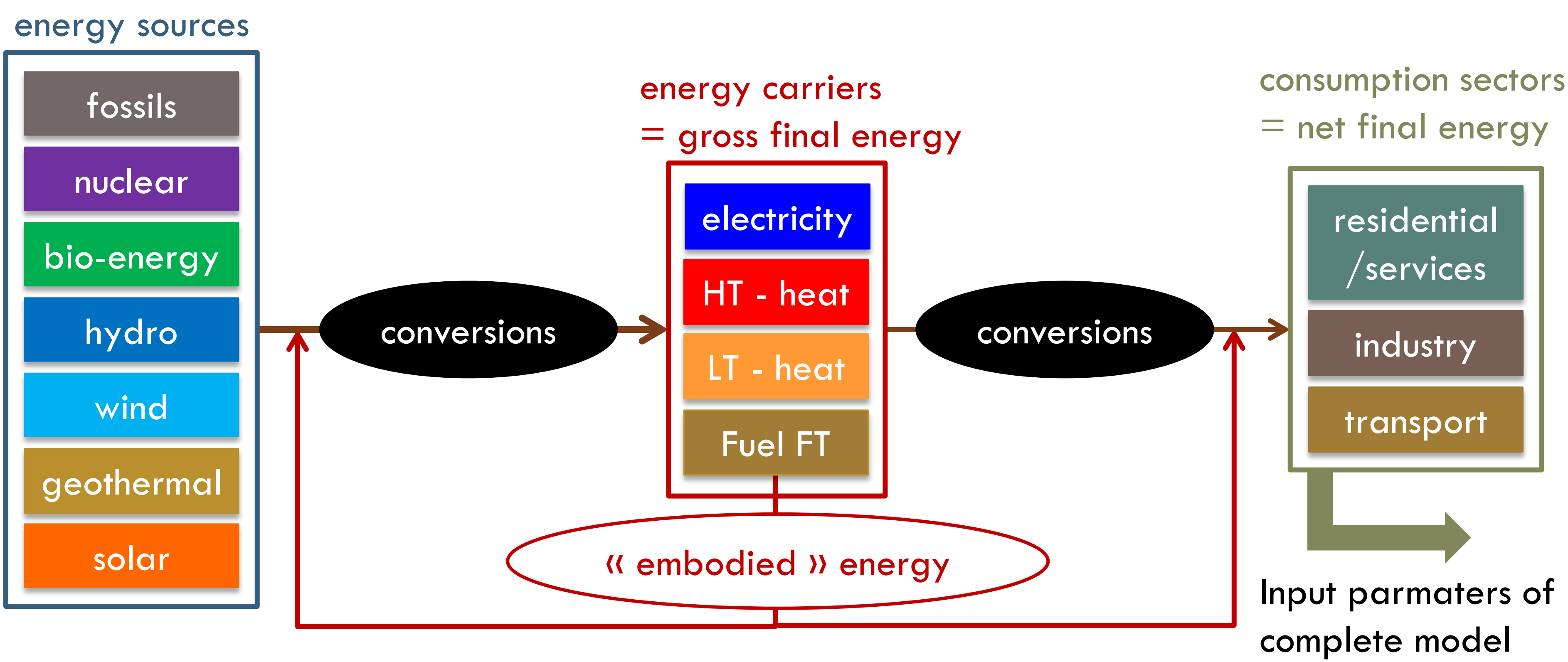
Energy sector description

- Energy sector considered as an economic production sector but treated in a first step separatly

➡ « physical » analysis of scenarios independently of economic model and hypothesis

- Energy sector described as a set of technologies

« source – energy carrier – energy end-use »

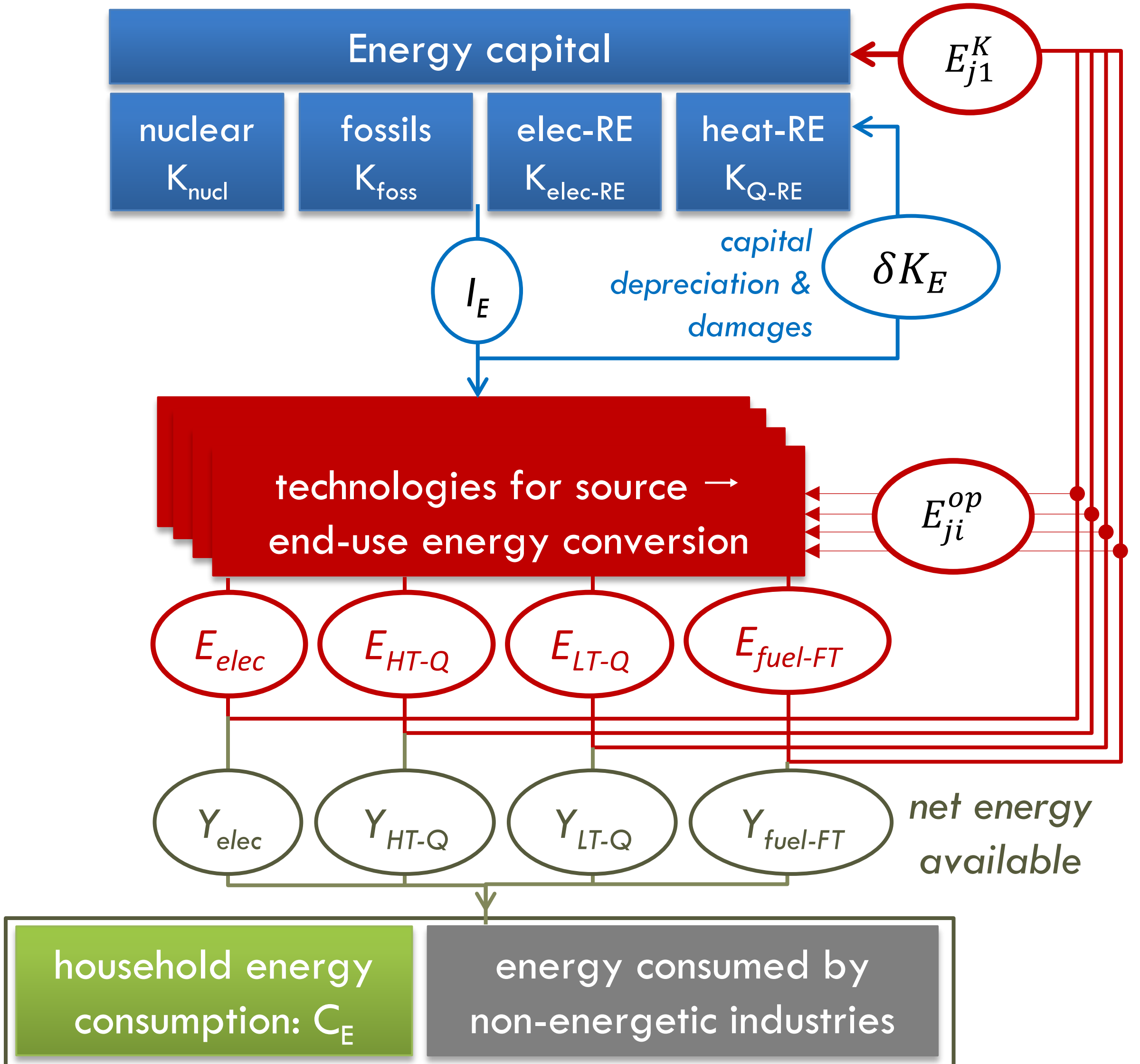


Energy sector modeling

- Translate economic quantities such as capital, investment, gross and net production in energy units to describe the transition of a given scenario

Economy	Energy
n sectors of commodities production	technologies called by scenarios to operate the energy transition fossil fuels → electricity biomass → fuel for transport solar → low-temperature heat
Capital K	energy facilities (K_E) running at full capacity to produce the gross total final energy (E) $E = \frac{K_E}{\nu_E}$ with $\frac{1}{\nu_E}$: energy produced / capital unit
Investment I	energy required (I_E) to construct new energy facilities $\left(\dot{K}_E\right)$ to increase the gross energy production and/or to replace the old ones (δK_E) $I_E = \dot{K}_E + \delta K_E$
Net prod. Y	net energy (Y_E) produced by the capital K_E once the energy consumed for the energy production itself deducted

- Energy sector modeling inspired by the economic model



- Energy transition scenario

Energy facilities evolution

- ✓ decline: $K_i \searrow$
- ✓ renewal: $K_i = \text{Cte}$
- ✓ deployment: $K_i \nearrow$

input parameter

Energy investment fixed by the scenario for each type of source i (= nucl, foss, elec-RE, Q-RE)

Energy carriers produced/source

Quantity of energy carriers j produced by each type of source i fixed by the scenario

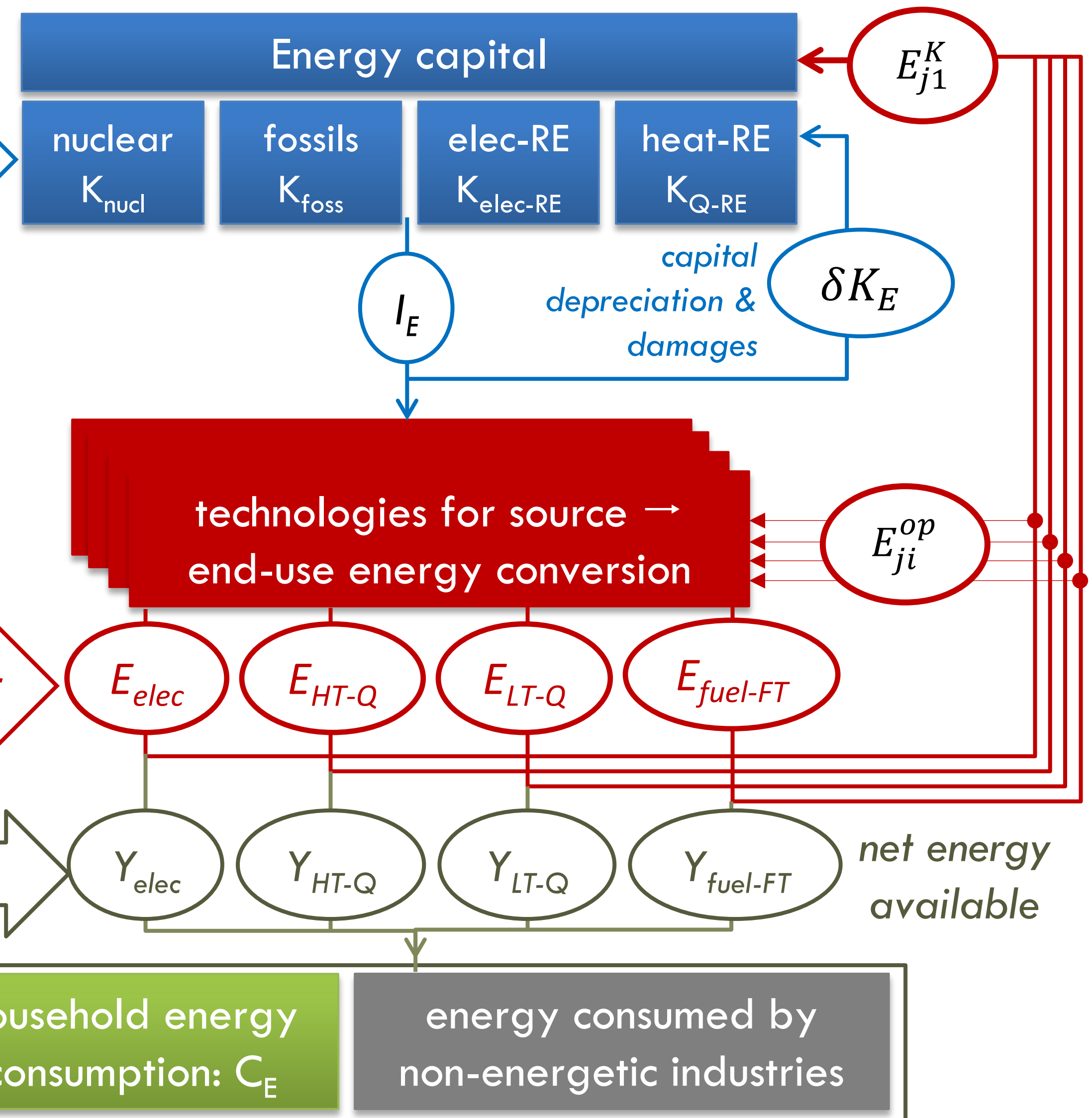
$$E_j = \sum_i \eta_{ji} E_i$$

input parameter

Energy consumption by household and non-energetic industries

= ?

- Energy sector modeling inspired by the economic model



- Identify the main technologies « source – carrier – use » called by the scenarios
- Quantify the « embodied » energy in terms of
  - Energy consumed for the facilities construction $\left(E_{j1}^{K}\right)$
  - Energy consumed by the facilities when they produce continuously energy from the source to the consumer $\left(E_{ji}^{op}\right)$

➡ Distinction between the energy self-consumed for the capital and for the operation

- For a given source, the embodied energy is different according the energy carrier that it produces

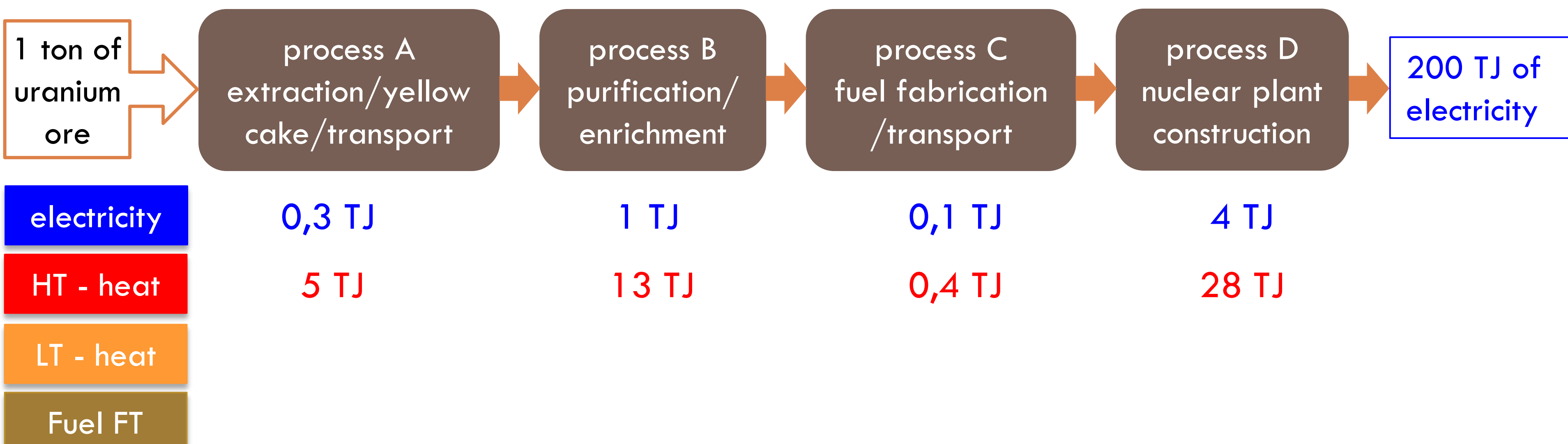
➡ Analysis based on the energy carriers in terms of quantities produced by the technologies and embodied energies consumed by these technologies themselves

Energy sector modeling / « Embodied » energy

- Methodology inspired from « Life Cycle Analysis » to take into account all the operations from « cradle to gate »
- Energy investment for each technology = energy consumed to synthesize the main materials used for the construction of the facilities and all their equipment

	concrete		steel		copper		aluminium	
	electricity	HT-Q	electricity	HT-Q	electricity	HT-Q	electricity	HT-Q
GJ/ton	0,2	1	1,4	11	30	10	50	5

<u>Embodied energy for nuclear electricity: investment</u>



- Energy self-consumed for the facilities operation

Embodied energy for nuclear electricity generation : operation

1 ton of uranium ore → process A extraction/yellow cake/transport → process B purification/enrichment → process C fuel fabrication /transport → process D nuclear plant operation → 200 TJ of electricity

	process A extraction/yellow cake/transport	process B purification/enrichment	process C fuel fabrication /transport	process D nuclear plant operation
electricity	0,2 TJ	0,2 TJ	0,1 TJ	9 TJ
HT - heat	2,3 TJ	0,2 TJ	0,004 TJ	2 TJ
LT - heat				
Fuel FT	0,4 TJ		0,004 TJ	

- Values about operation and investment come from multiple information sources (data base, private communications with experts, reports, …)

➡ huge lack of information and important discrepancies between values when they exist, hypotheses non explained,…

Energy sector modeling / « Embodied » energy

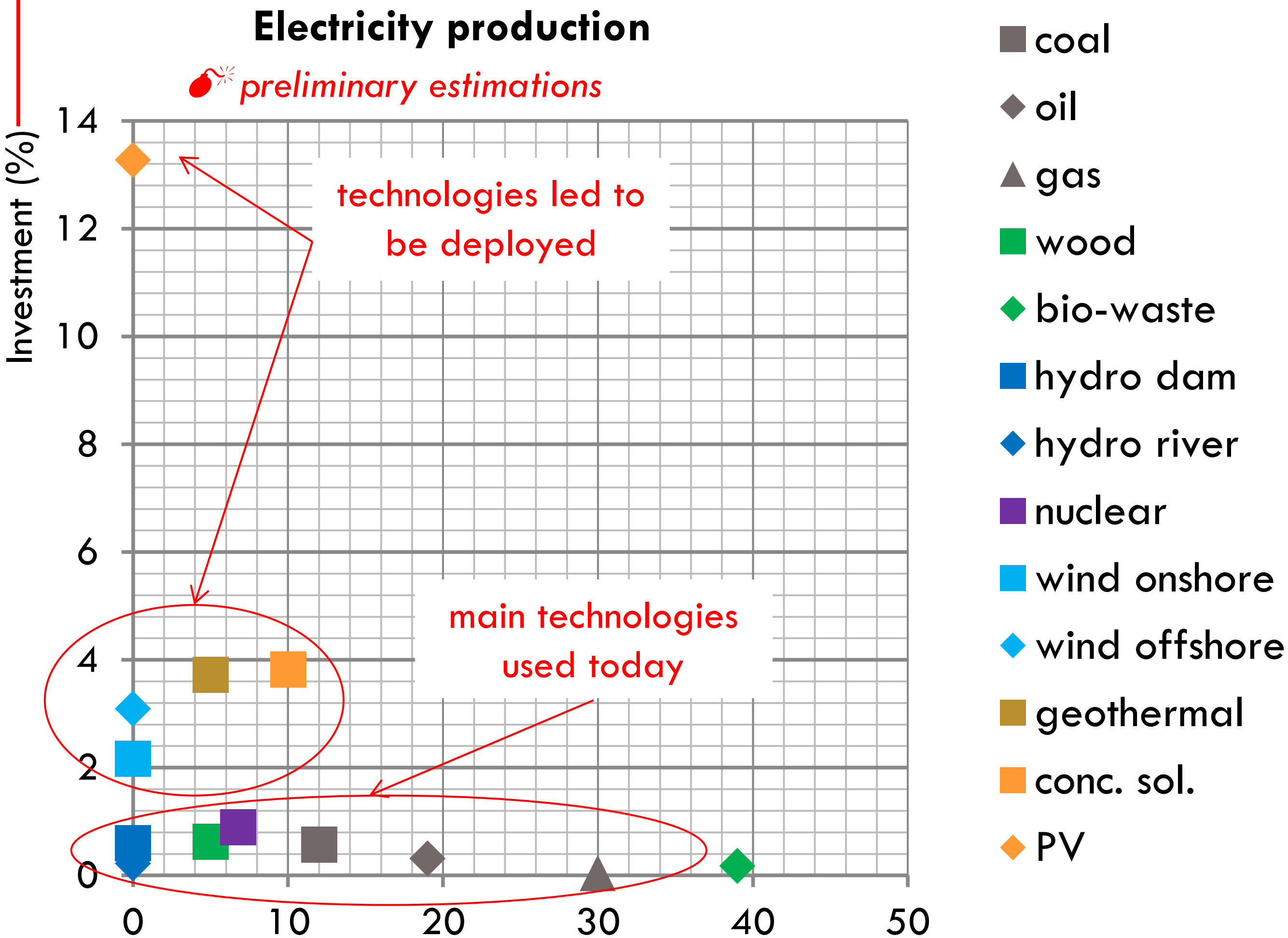
- from the analysis of different scenarios 31 technologies « source – carrier » involved in the energy transition

	Fuel FT	LT-heat	HT-heat	electricity
energy carriers → energy sources	oil	coal	coal	coal
	bio-ethanol	oil	oil	oil
	bio-diesel	gas	gas	gas
	algae	wood	wood	wood
		bio-waste	bio-waste	bio-waste
		geothermal	geothermal	hydro_dam
		thermal solar	conc. solar	hydro_river
				nuclear
				wind_onshore
				wind_offshore
				geothermal
				conc. solar
				photovoltaïc

- Quantities to characterize each technology i « source – carrier »
  - $E_{consumed}^{K_i}$: energy investment/capital unit (joules)
  - $E_{consumed}^{Op_i}$: energy consumed for the operation (joules)
  - $E_{produced}^{tech_i} = P_{installed} \times load\ factor \times 1\ year\ (joules/year)$
  - Life time (years)

« Embodied » energy / investment vs operation

$$\text{Investment (\%)} = \frac{\text{energy investment/capital unit}}{\text{total energy produced/capital unit}} = \frac{E^{K_i}_{consumed}}{E^{tech_i}_{produced} \times life\ time} = \frac{1}{\text{EROI}}$$



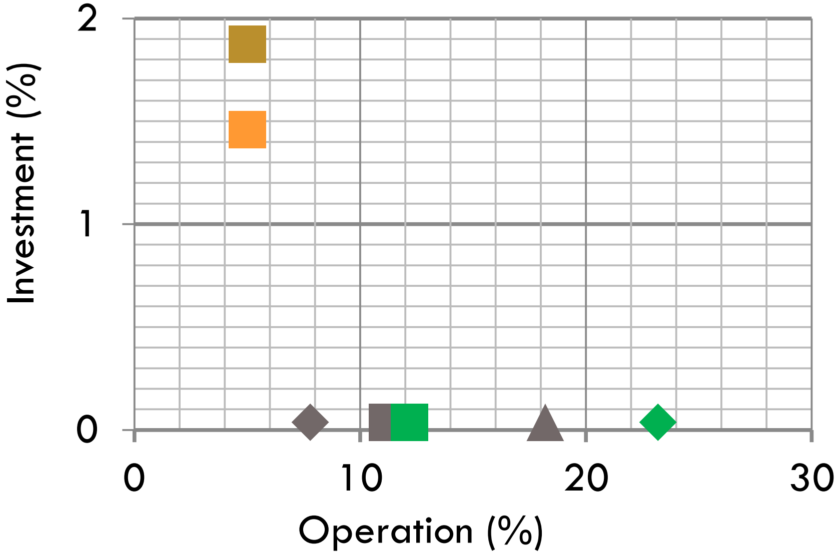
Life time (year)	Load factor (%)
20	85
20	85
20	85
20	85
20	85
80	30
80	85
40	85
20	20
20	20
20	85
20	40
20	20

$$\text{Operation (\%)} = \frac{\text{energy consumed for energy production}}{\text{energy produced}} = \frac{E^{Op_i}_{consumed}}{E^{tech_i}_{produced}}$$

« Embodied » energy / investment vs operation

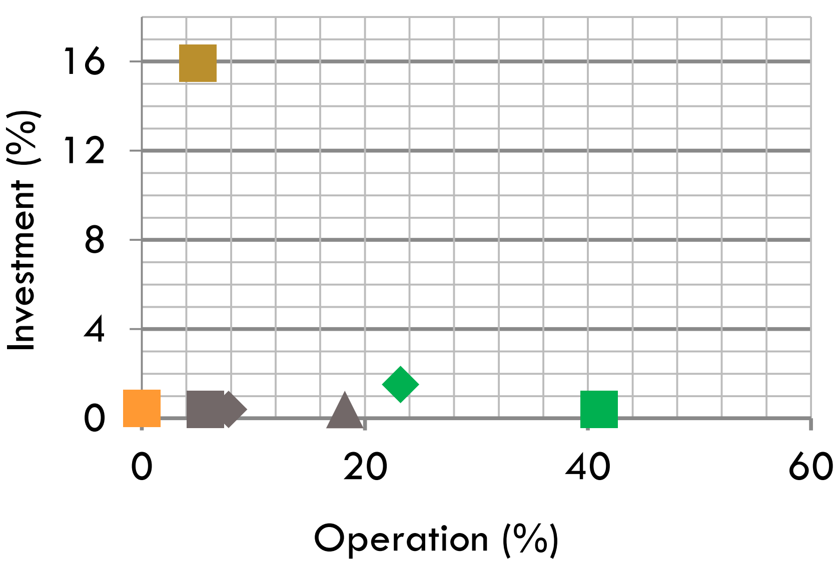
HT - heat production

preliminary estimations



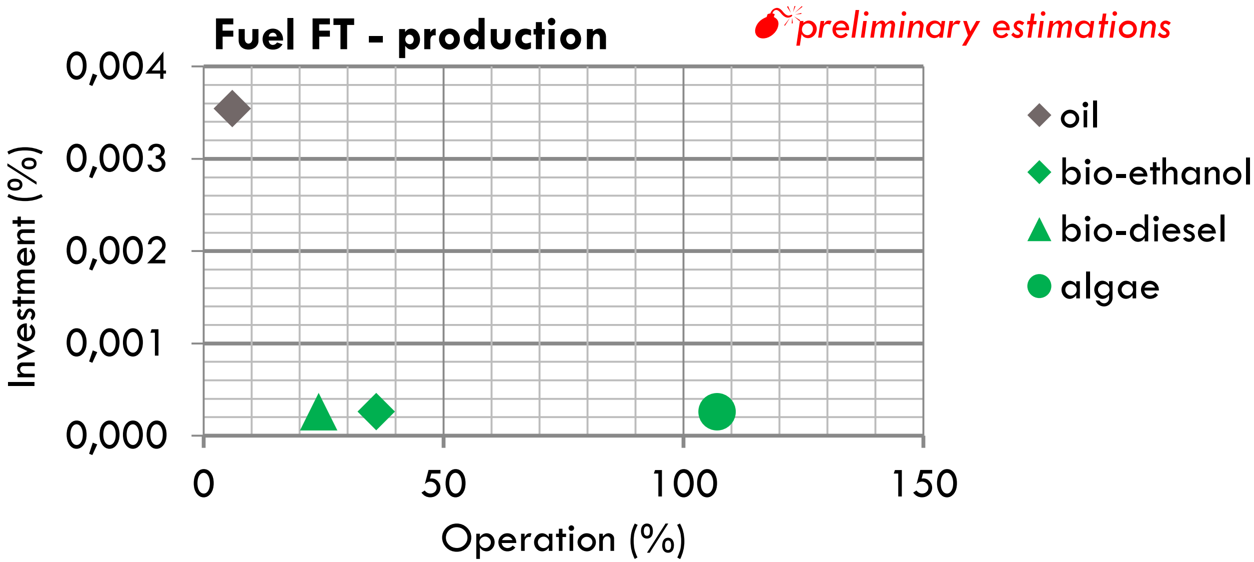
	Life time (y)	Load factor (%)
coal	20	85
oil	20	85
gas	20	85
wood	20	85
bio-waste	20	85
geothermal	20	85
conc. sol.	20	40

LT - heat production



	Life time (y)	Load factor (%)
coal	20	10
oil	20	10
gas	20	10
wood	20	10
bio-waste	20	10
geothermal	20	10
therm. sol.	20	15

« Embodied » energy / investment vs operation



Life time (y)	Load factor (%)
20	85
20	85
20	85
20	85

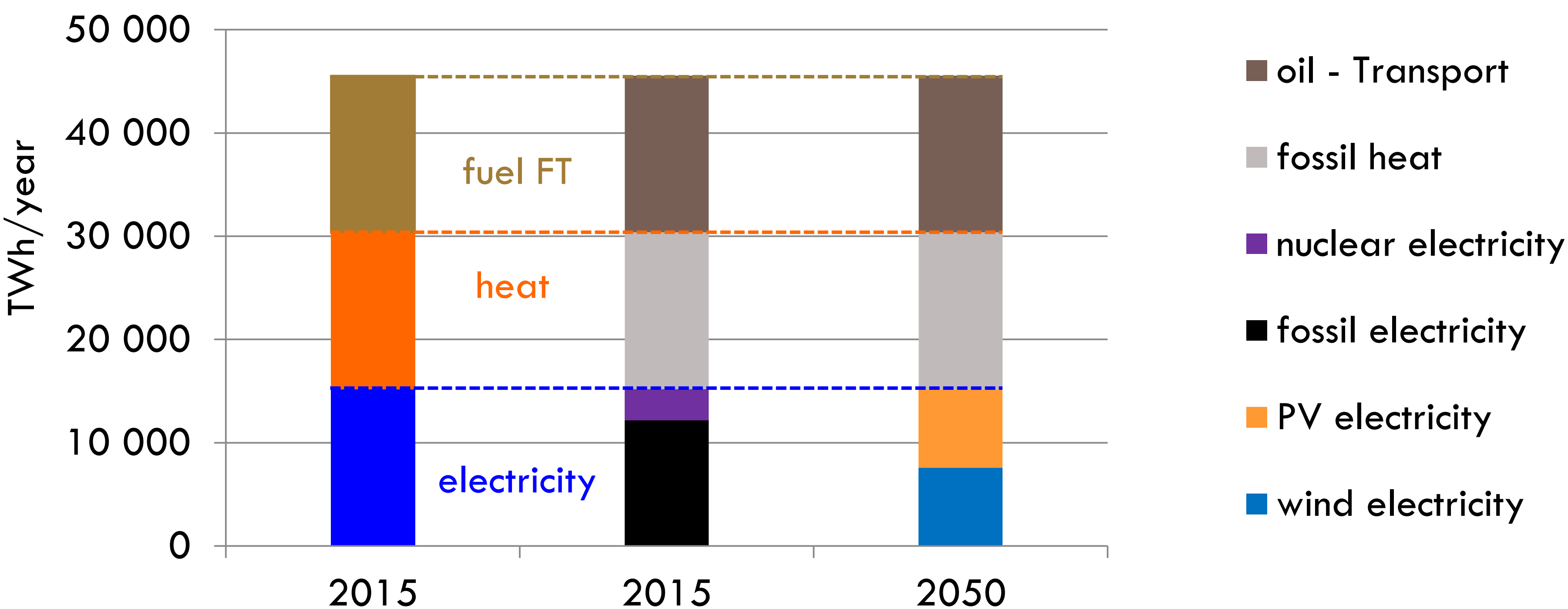
All energy investment values are consistent between technologies but very underestimated compared to values found in literature

- What is not taken into account
  - storage for intermittent sources
  - CCS technology
  - installation dismantling & waste treatment
  - investment for end-use energy consumption
  - transport of the final energy carrier to the user

➡ For more realistic values: $E_{consumed}^{K_i} \times 3 \rightarrow \times 5$ (?)

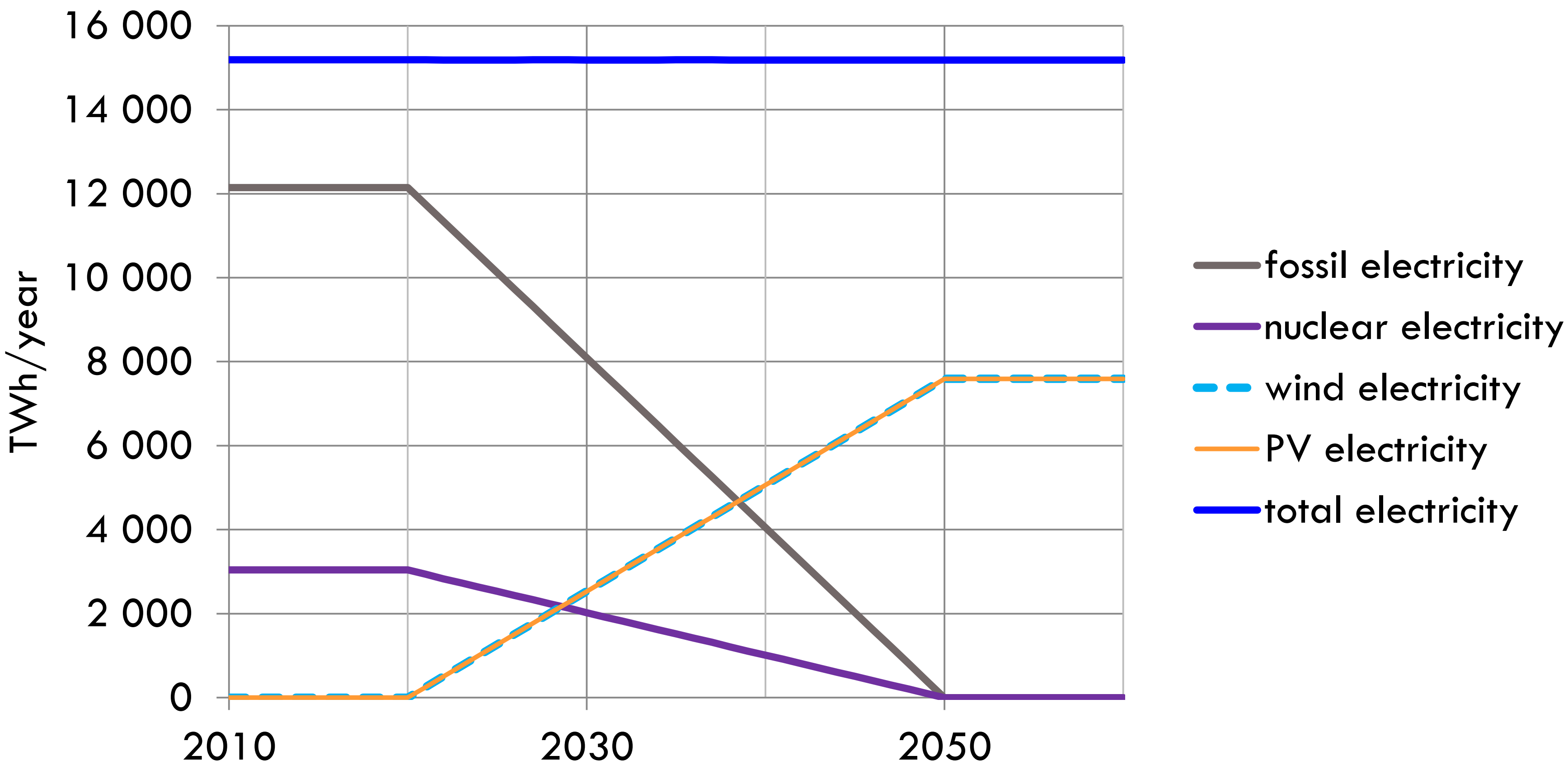
Mecanisms of the modeling / a simplified example of scenario

- Gross final energy and carrier generation kept constant from 2015 → 2050
  - 1/3 electricity – 1/3 heat – 1/3 fuel for transport
  - In 2015: fossils = 93 % of total gross final energy
  - during the transition
    - fossil and nuclear electricity ↘ 0 replaced by 50% PV and 50% wind
    - fossil heat & oil for transport kept constant
  - In 2050: fossils = 67 % of total gross final energy

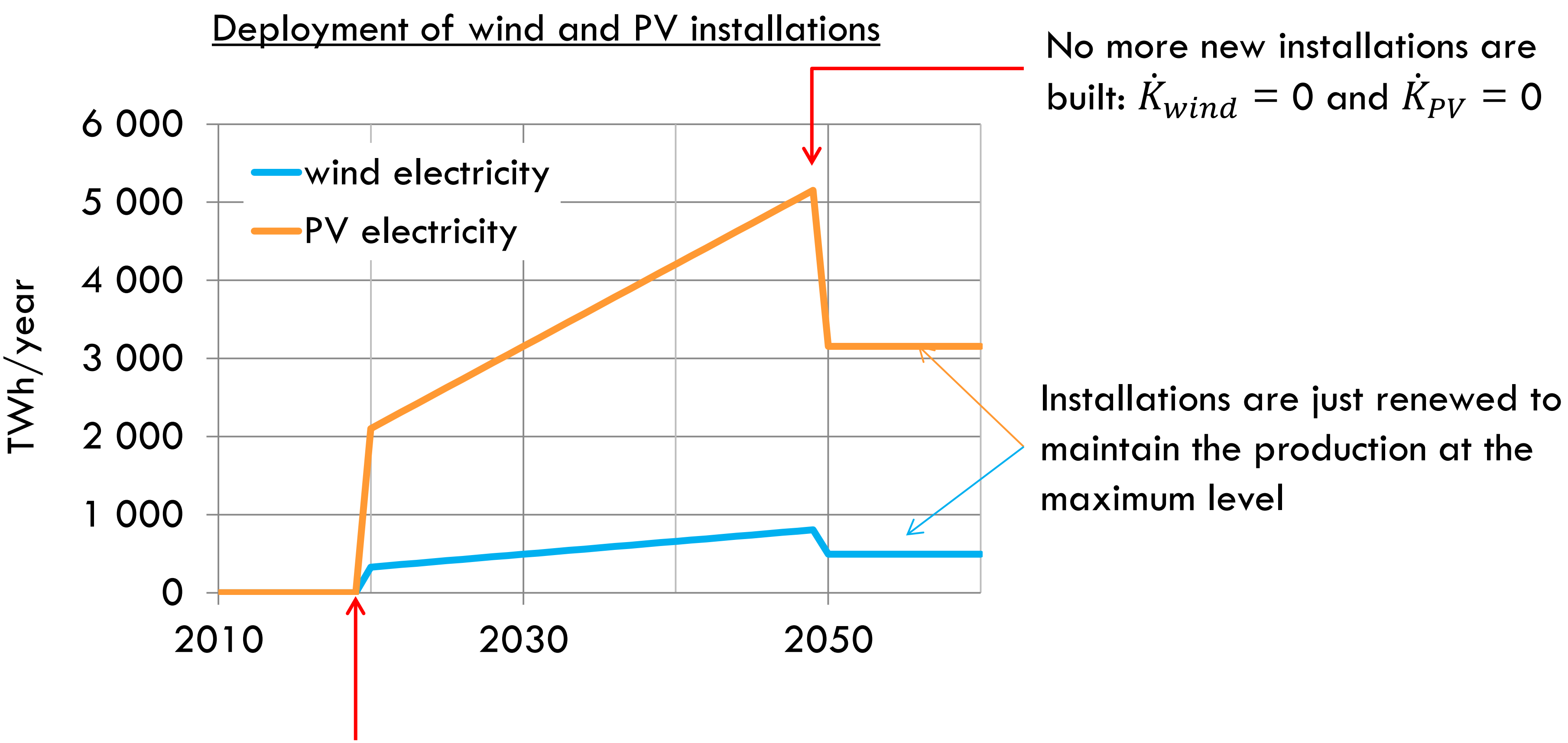


Mecanisms of the modeling / a simplified example of scenario

- During the transition, gross energy « source - carrier » generation is supposed to vary linearly



- Energy investment / « wind – electricity » & « PV – electricity »



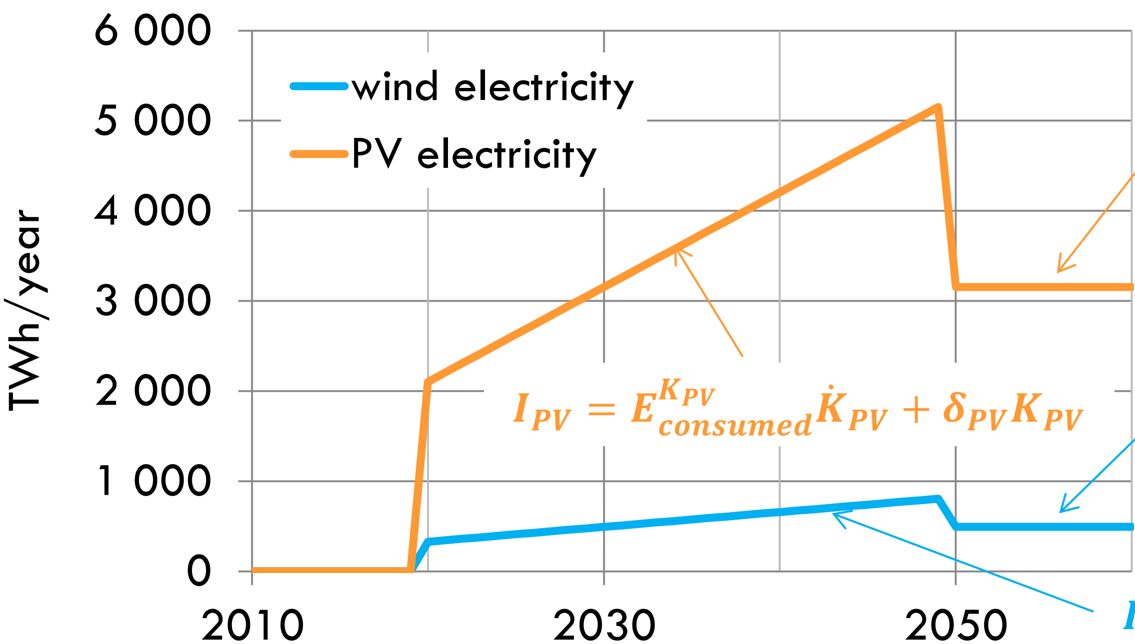
- Construction of new installations = $\dot{K}_{wind}$ and $\dot{K}_{PV} > 0$

➡ Energy consumed for the construction = $E^{K_{wind}}_{consumed}\dot{K}_{wind}$ and $E^{K_{PV}}_{consumed}\dot{K}_{PV}$

Mecanisms of the modeling / a simplified example of scenario

- Energy investment / « wind – electricity » & « PV – electricity »

Deployment of wind and PV installations



$$I_{PV} = \delta_{PV} K_{PV} = \frac{E_{consumed}^{K_{PV}}}{LT_{PV}} K_{PV}$$

$$I_{wind} = \delta_{wind} K_{wind} = \frac{E_{consumed}^{K_{wind}}}{LT_{wind}} K_{wind}$$

$$I_{wind} = E_{consumed}^{K_{wind}} \dot{K}_{wind} + \delta_{wind} K_{wind}$$

- As soon as the installations are built
  - energy is « capitalized » each year to replace them at the end of their life
  - capital is depreciated

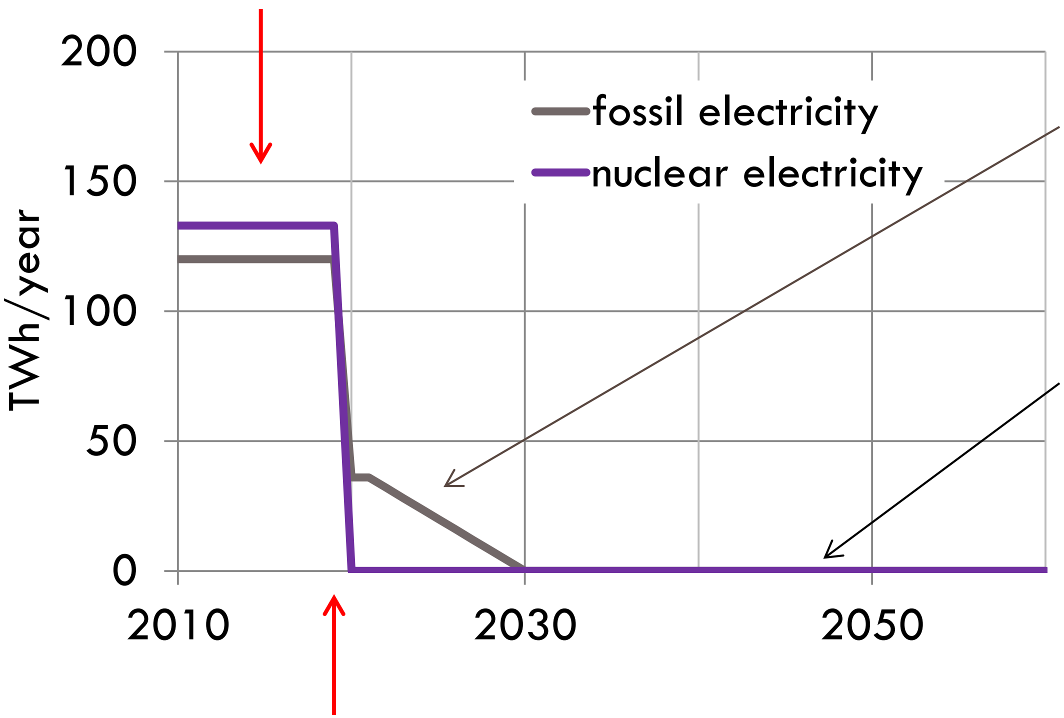
➡ Energy consumed to renew the installations = $\delta_{wind} K_{wind}$ and $\delta_{PV} K_{PV}$

with $\delta_{wind,PV} K_{wind,PV} = \frac{E_{consumed}^{K_{wind,PV}}}{LT_{wind,PV}} K_{wind,PV}$

- Energetic investment / « fossil – electricity » and « nuclear – electricity »

  <u>Decrease of fossil and nuclear installations dedicated to electricity generation</u>

<u>Before energy transition</u>: installations are just renewed to maintain the production at the maximum level: $I_{fos.,nucl.} = \delta_{fos.,nucl.}.K_{fos.,nucl.} = \frac{E_{consumed}^{K_{fos.,nucl.}}}{LT_{fos.,nucl.}} K_{fos.,nucl.}$



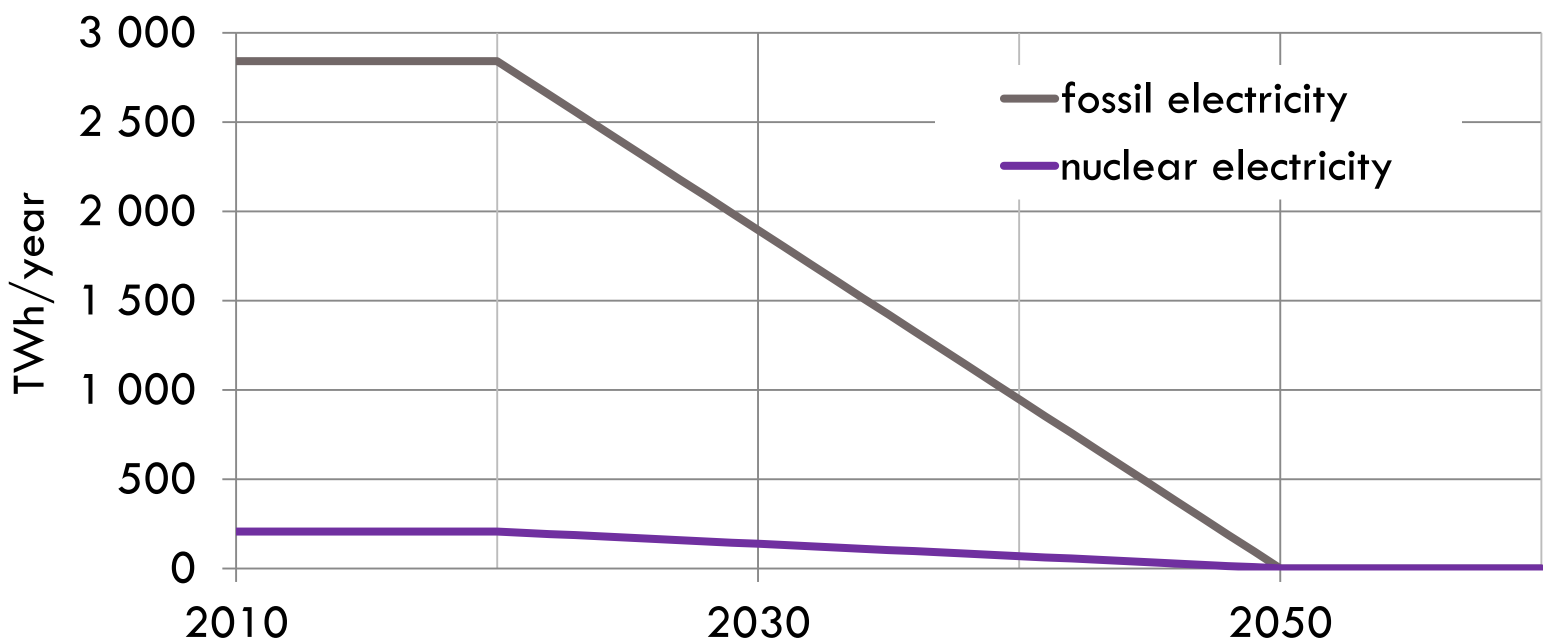
remaining fossils installations have to be renewed
$I_{fos} = \delta_{fos}.K_{fos}$

remaining nuclear and fossil plants are not renewed, the production decreases gradually until the end of their life: $I_{fos} = 0$ and $I_{nucl} = 0$

- Fossil and nuclear facilities stop producing

  ➡ $\dot{K}_{fos}$ and $\dot{K}_{nucl} < 0$, K_{fos} and K_{nucl} ↘ ➡ $I_{fos.,nucl.}$ ↘ abruptly

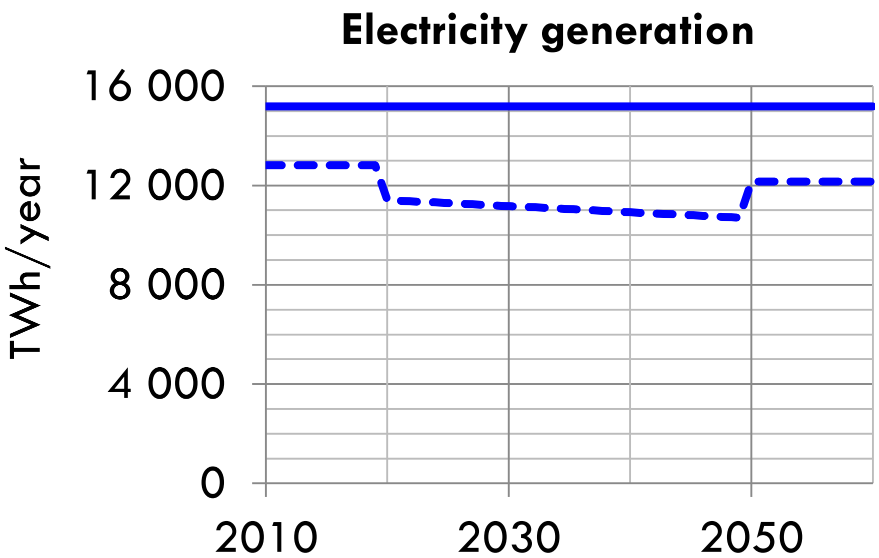
- Embodied energy for operation/ « source – carrier »
  - wind and PV: energy consumed for operation = 0
  - nuclear & fossils: energy consumed for operation decreases gradually as installations stop producing

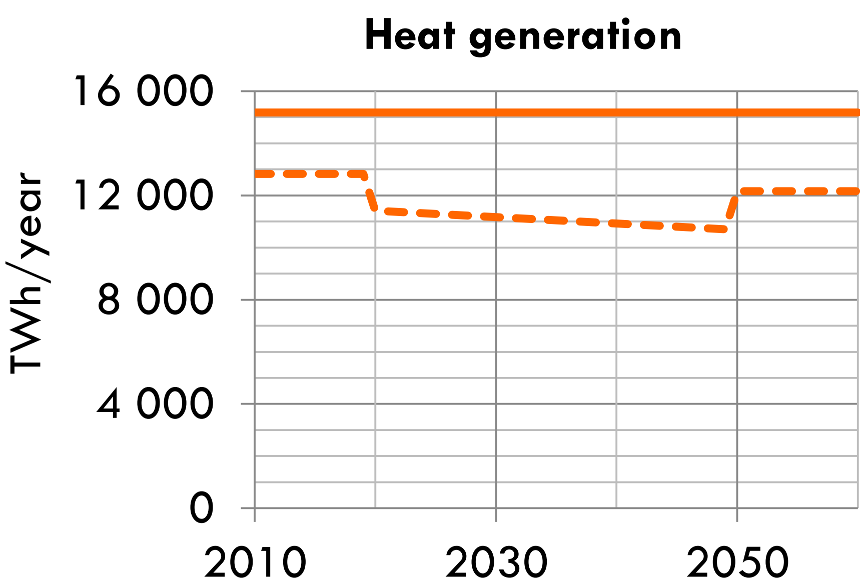


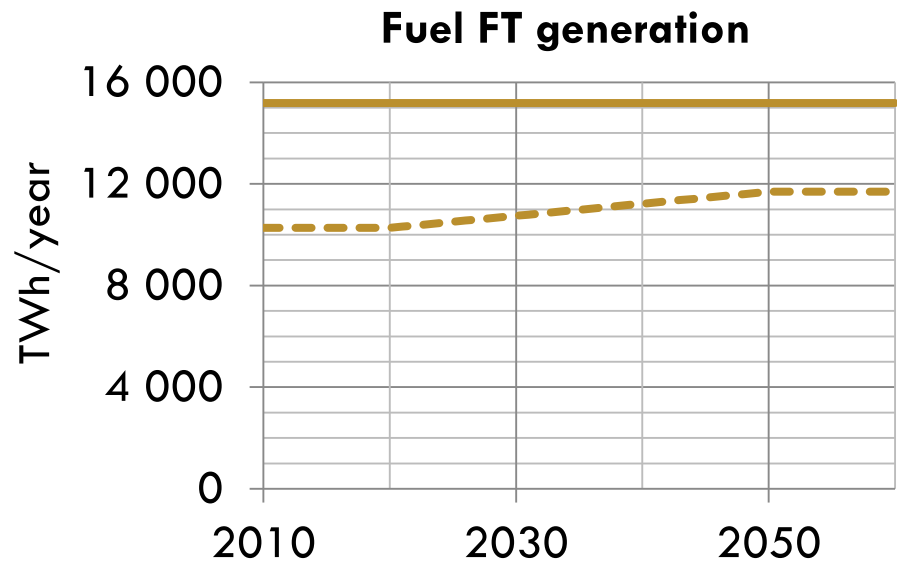
💣 fossil-heat & oil-transport: no change in the production so embodied energy for operation and investment remain constant

Mecanisms of the modeling / a simplified example of scenario

- Gross & net total production/ carrier







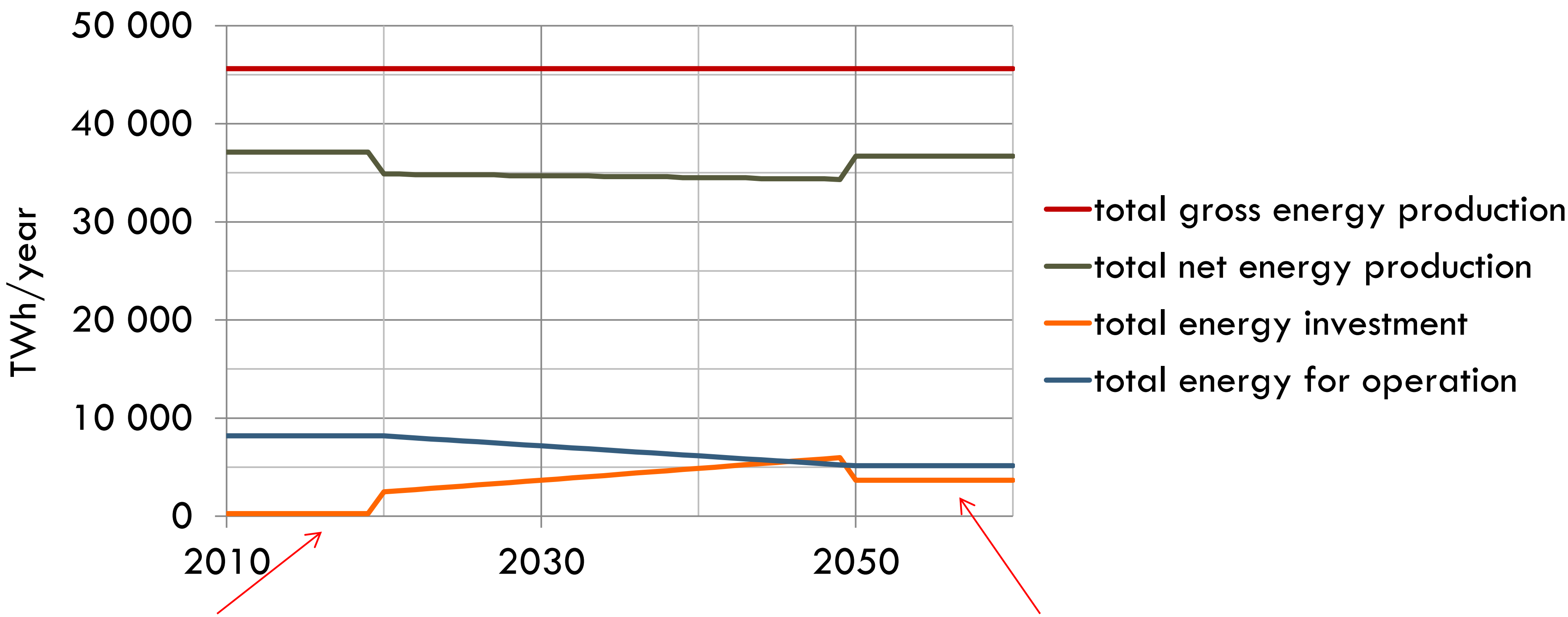
✓ The net fuel FT production increases as it is less consumed by the new energy mix for its capital & operation

✓ Electricity and heat are the most important carriers consumed as embodied energy during the transition and for the new energy mix

➡ energy finally available in the form of fuel, heat and electricity (net carrier production) for household and non energetic industry is different from the initial distribution

Mecanisms of the modeling / a simplified example of scenario

- Gross & net total production / investment & operation



<u>Before the transition</u>

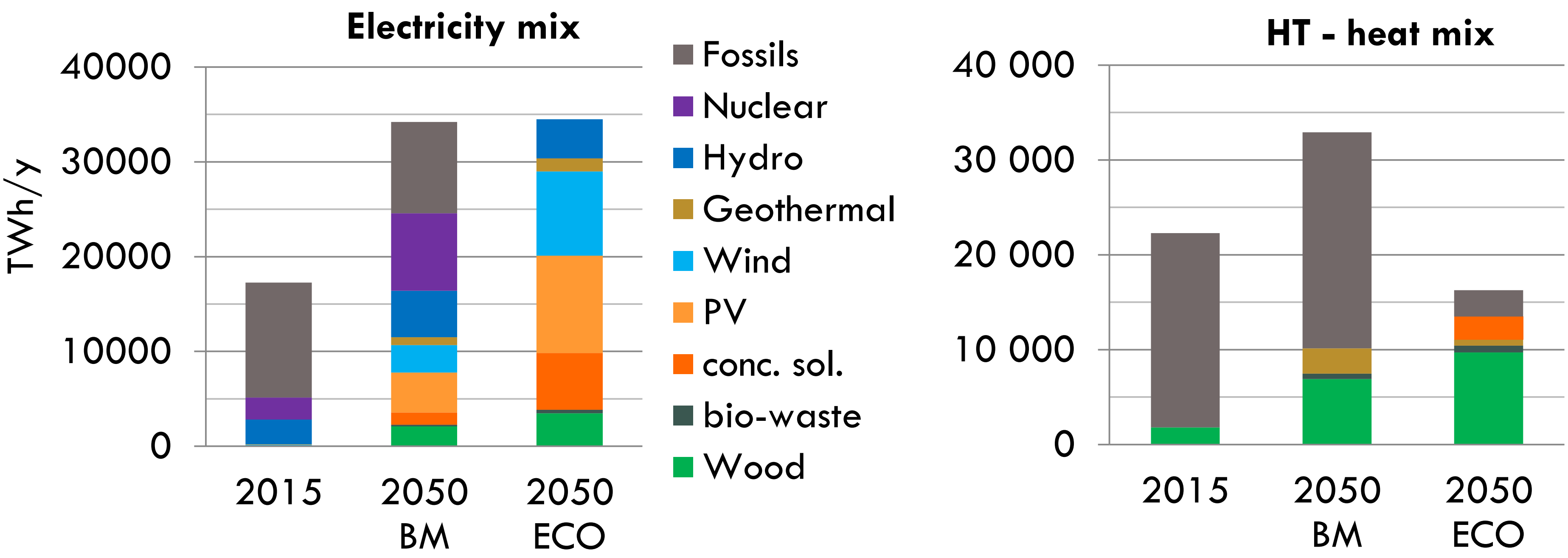
- ✓ total net final energy ~ 81% of the gross final energy
- ✓ energy to renew the capital < 1% of the gross final energy
- ✓ energy for operation ~ 18% of the gross final energy

<u>After the transition</u>

- ✓ total net final energy ~ 81% of the gross final energy
- ✓ energy to renew the capital ~ 8% of the gross final energy
- ✓ energy for operation ~ 11% of the gross final energy

Sensitivity to different energy transition scenarios

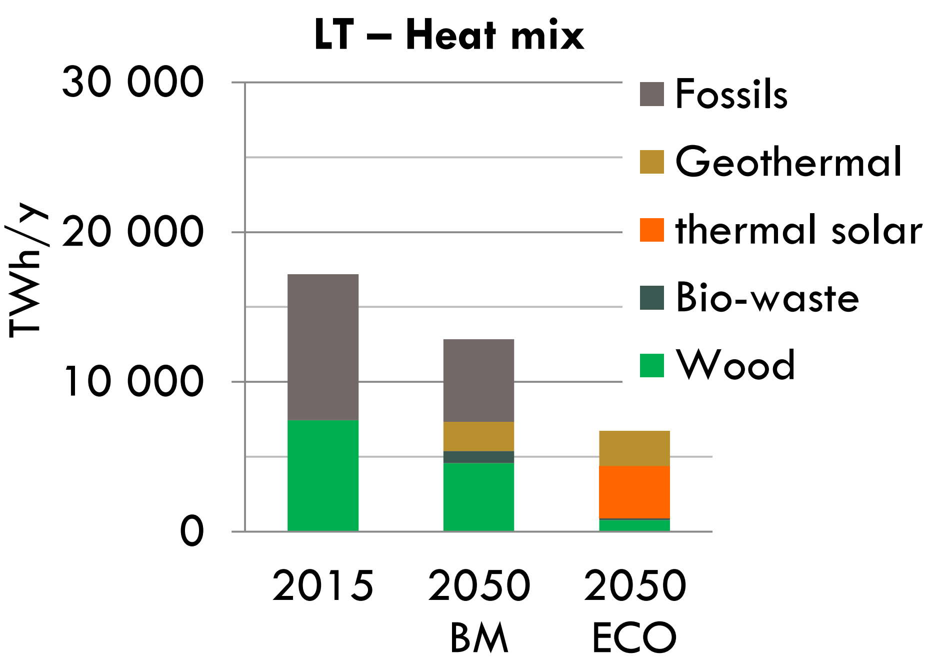
- 2 scenarios analyzed: BLUEMAP-IEA & ECOFYS-WWF with the same objective to reduce CO_2 emissions
  - 2 different energy source mix
  - 2 different gross energy carrier productions

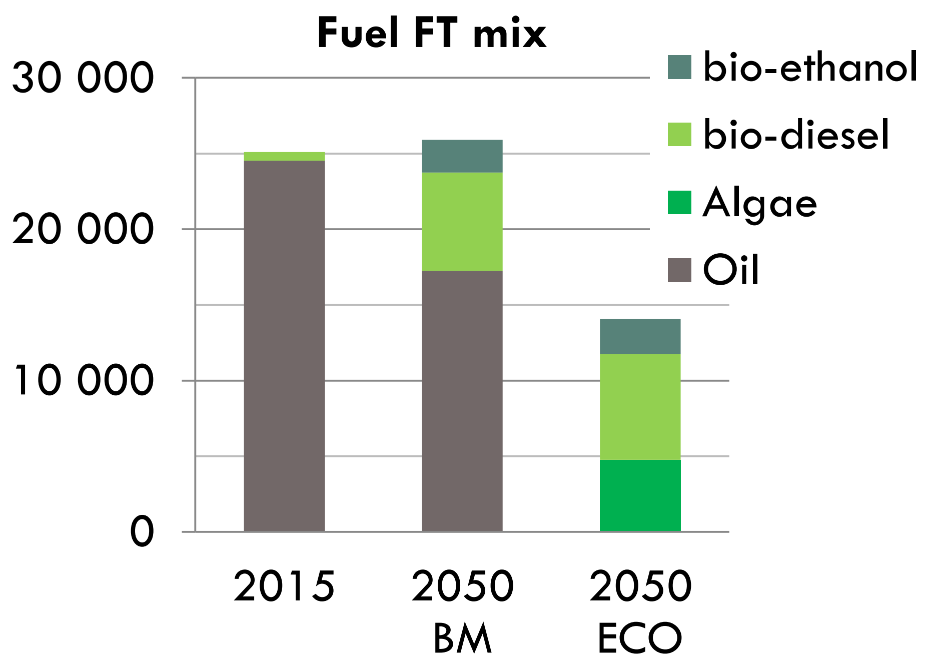


ECOFYS – WWF scenario

- ✓ No more fossil and nuclear electricity
- ✓ Strong bio-energy and renewable electricity deployments
- ✓ Much more less HT-heat than today

Sensitivity to different energy transition scenarios





ECOFYS – WWF scenario

- ✓ No more fossil for LT-heat and fuel for transport
- ✓ Much more less LT-heat and fuel for transport than today

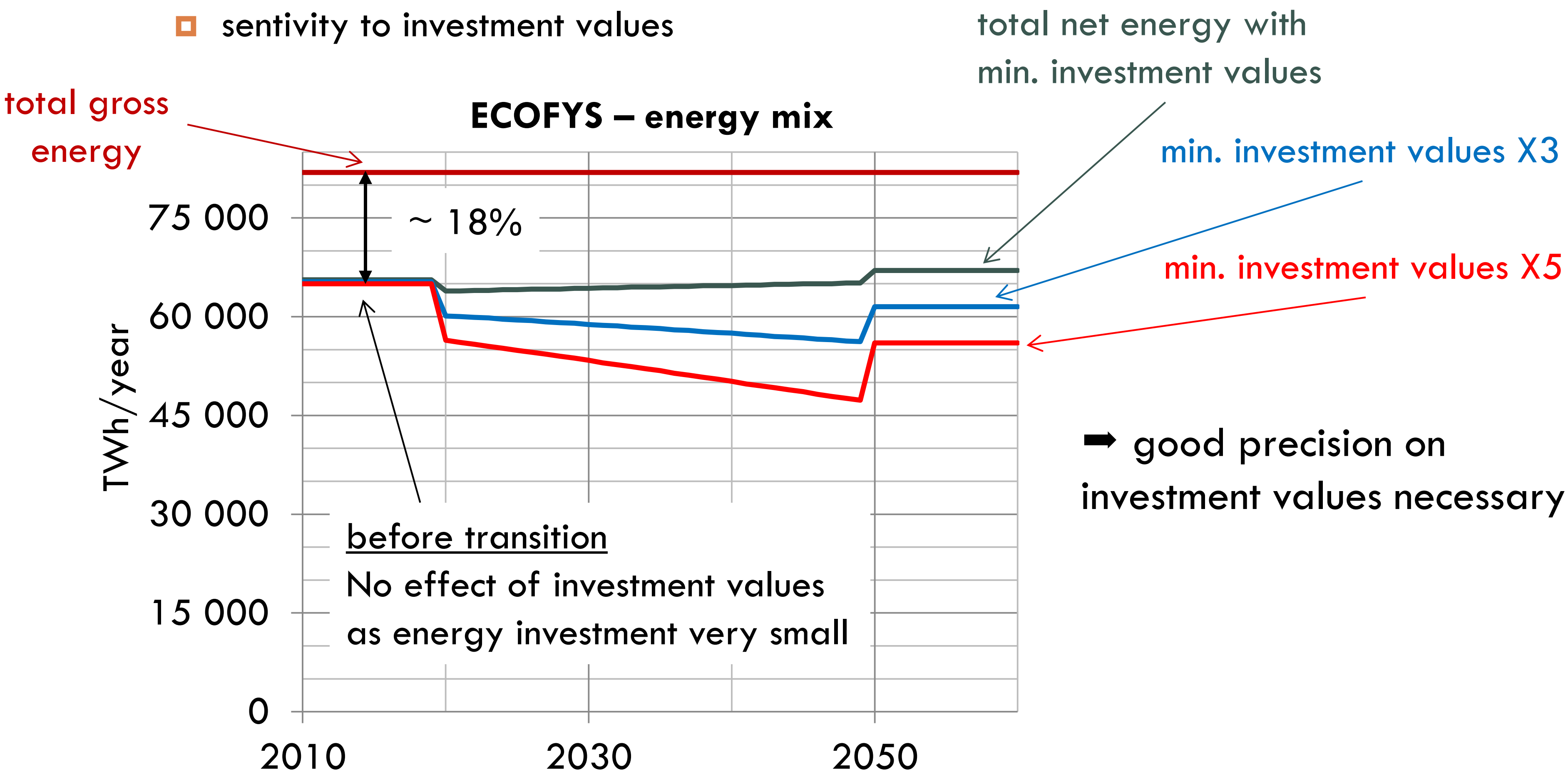
- Total gross energy production
  - Today ~ 82 000 TWh/year
  - BLUEMAP – 2050 ~ 106 000 TWh/year (+ 29%)
  - ECOFYS – 2050 ~ 72 000 TWh/year (- 12%)

Sensitivity to different energy transition scenarios

- First step: total final energy kept constant for both scenarios at the same value as today

➡ Difference between gross and net energy productions depend on the energy mix only

- sentivity to investment values



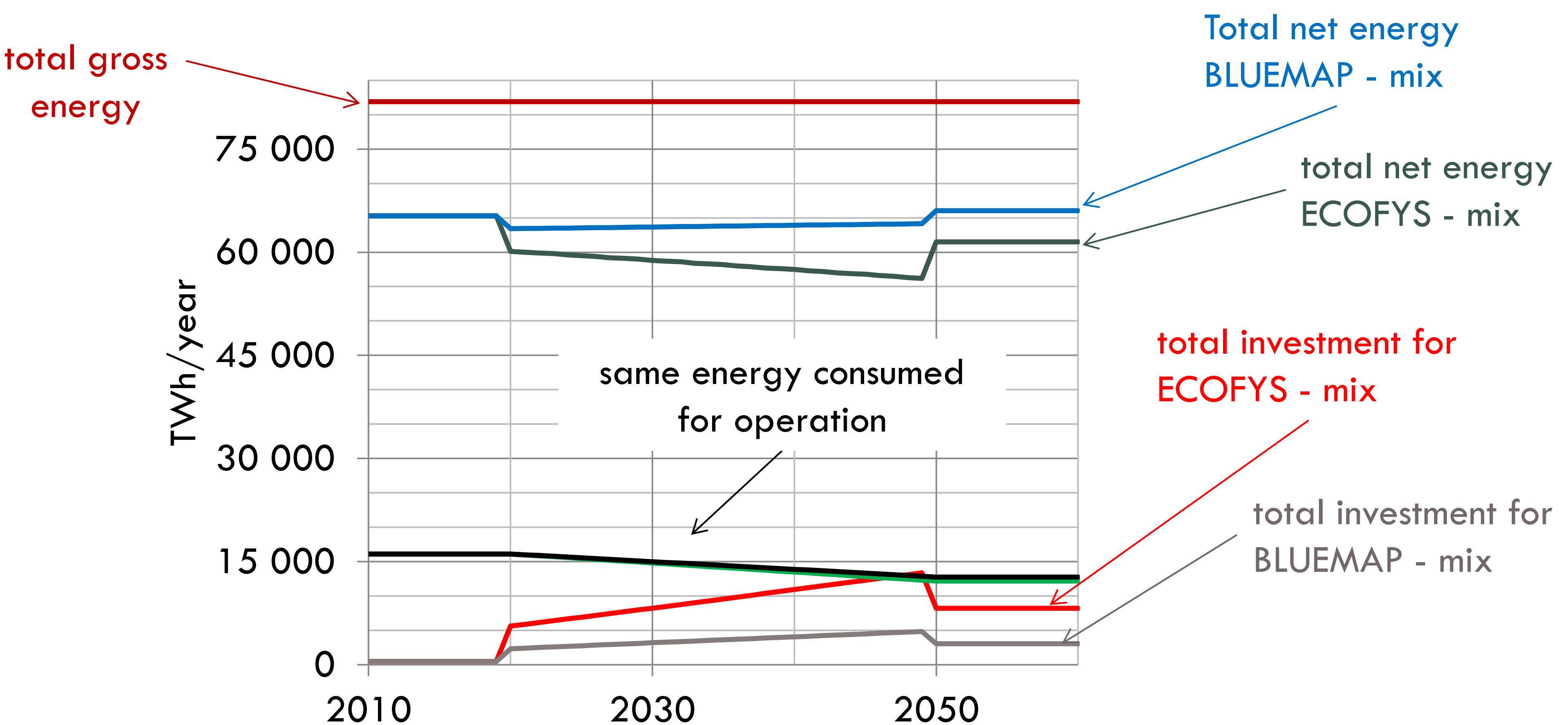
➡ good precision on investment values necessary

Sensitivity to different energy transition scenarios

- First step: total final energy kept constant for both scenarios at the same value as today

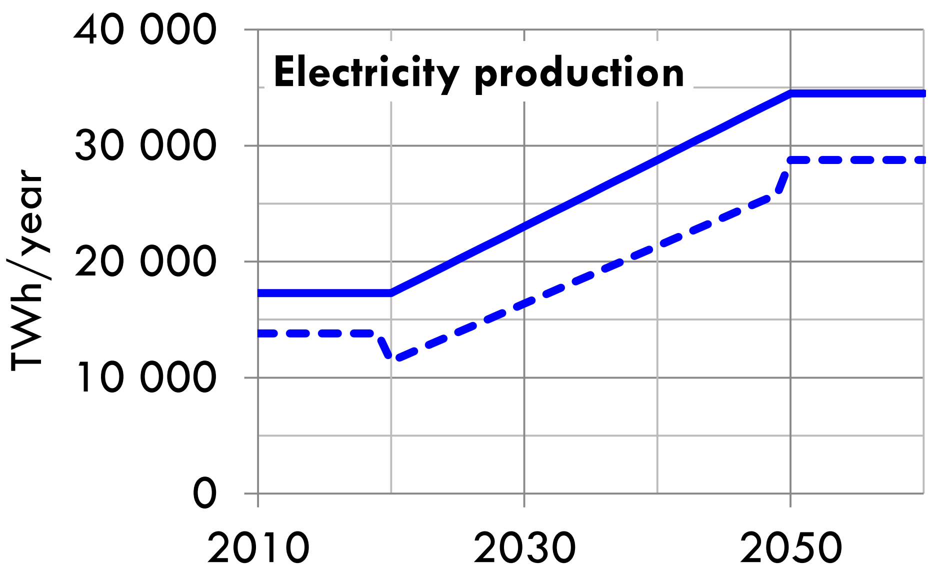
➡ Difference between gross and net energy productions depend on the energy mix only

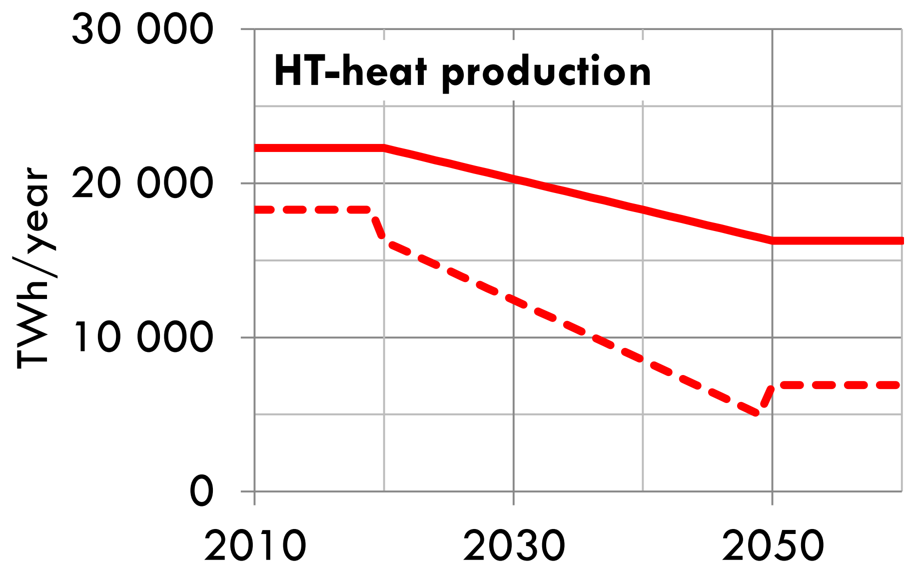
  - sentivity to different energy mix with investment values x3



Sensitivity to different energy transition scenarios

- Results for ECOFYS-scenario: gross & net total production / energy carrier (with minimum investment x3)





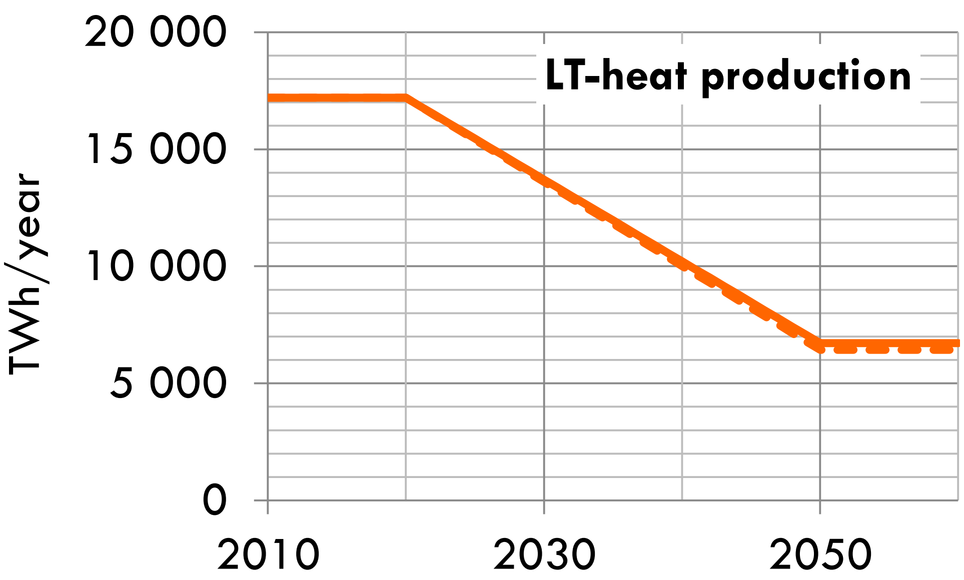
✓ Electricity and HT – heat are the most important energy carriers consumed during the transition (initial hypothesis/energy investment)

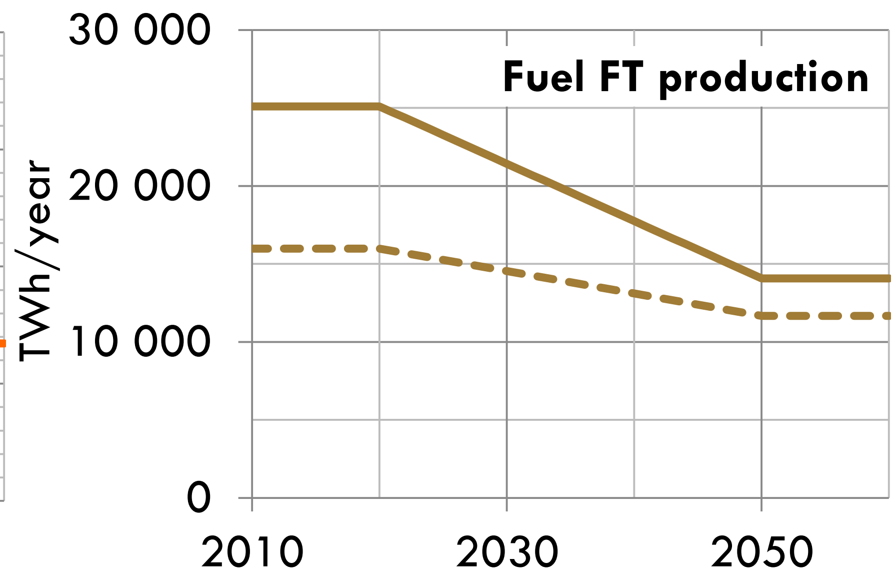
➡ gross and net electricity follow the same trend

➡ HT – heat is strongly consumed during the transition and after the transition the net production remains very low

Sensitivity to different energy transition scenarios

- Results for ECOFYS-scenario: gross & net total production / energy carrier

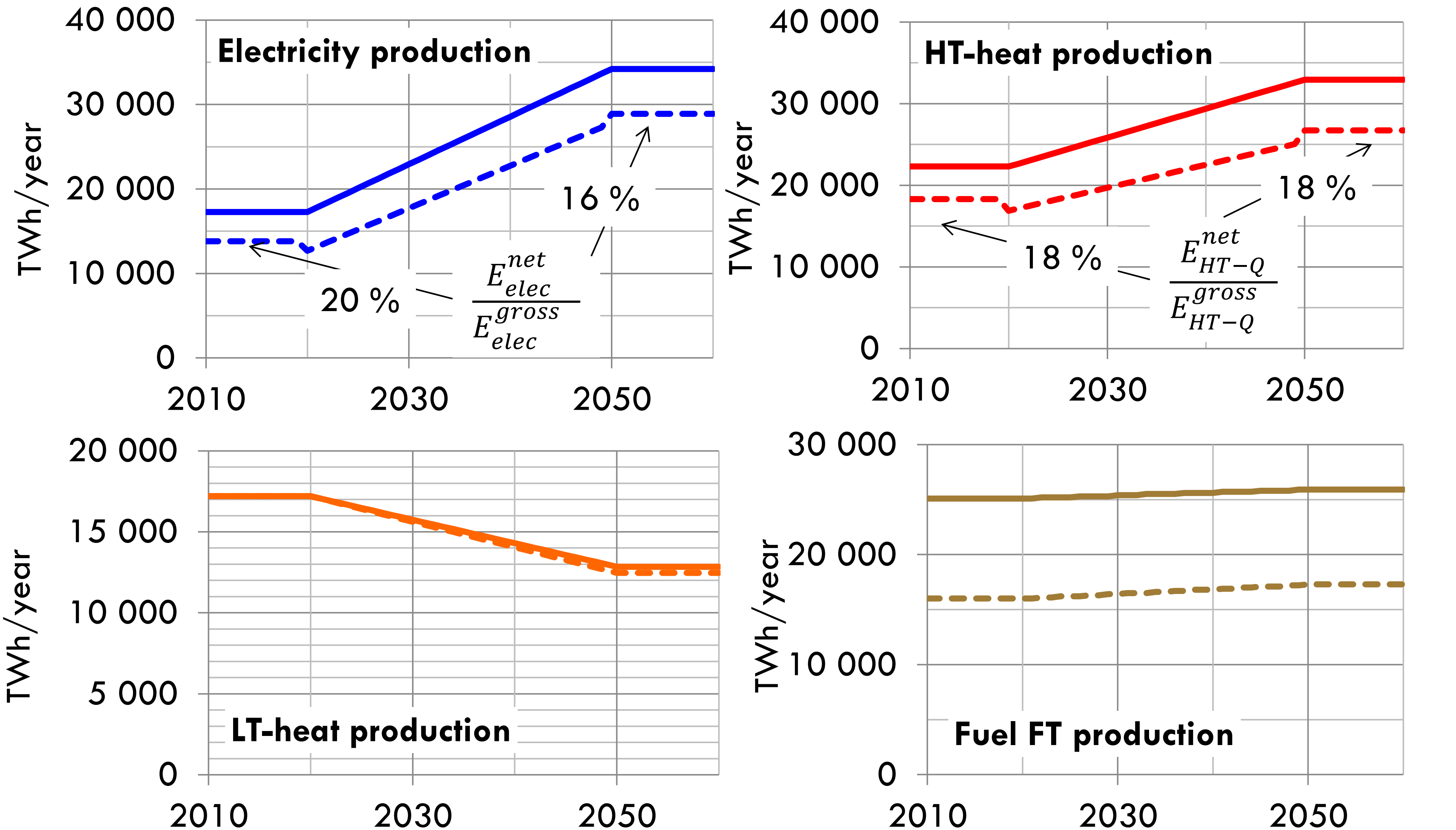




- ✓ LT – heat as embodied energy is very low
- ✓ Fuel-FT as embodied energy is less consumed by the new energy mix

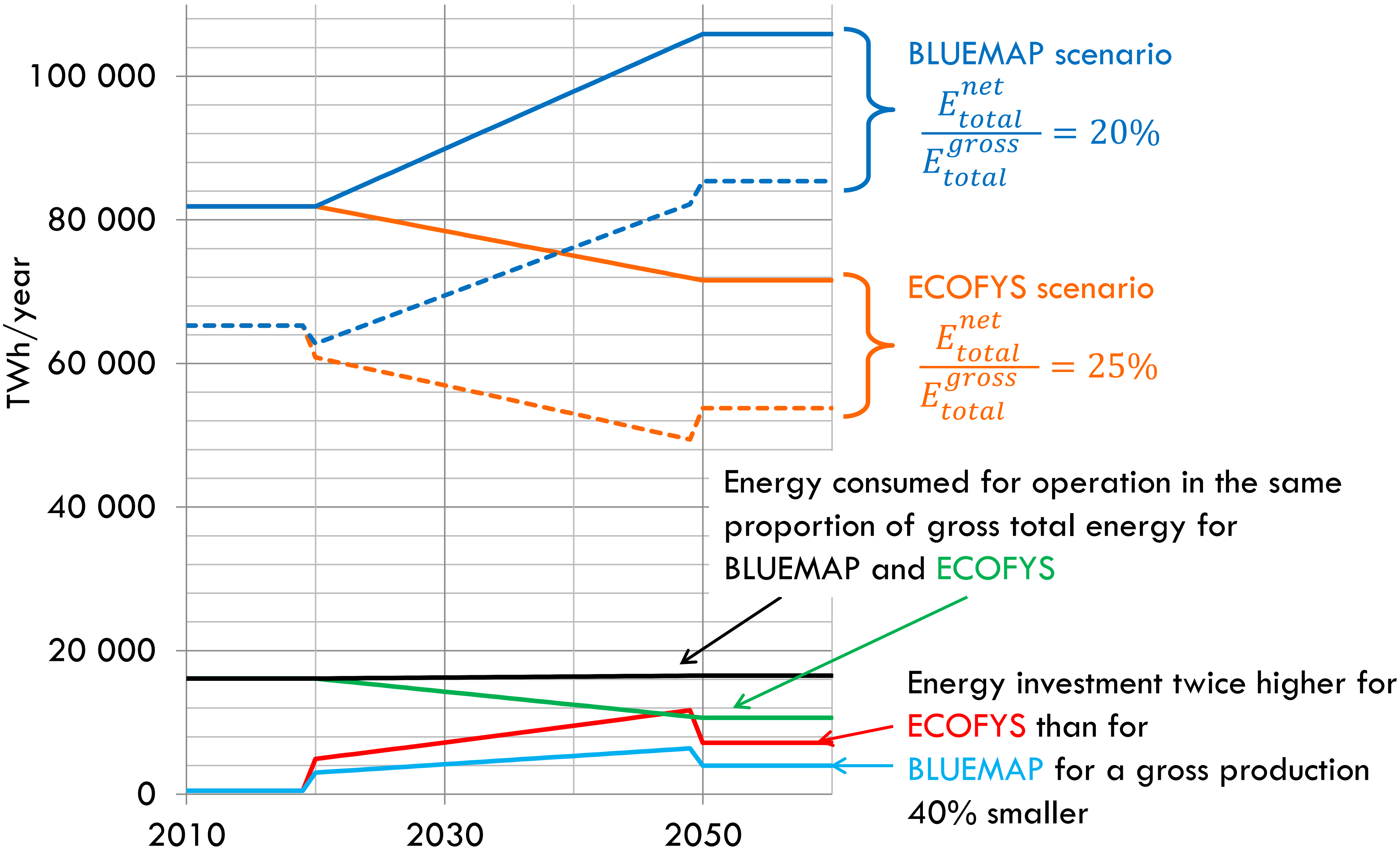
Sensitivity to different energy transition scenarios

- Results for BLUEMAP-scenario: gross & net total production / carrier (with minimum investment x3)



Sensitivity to different energy transition scenarios

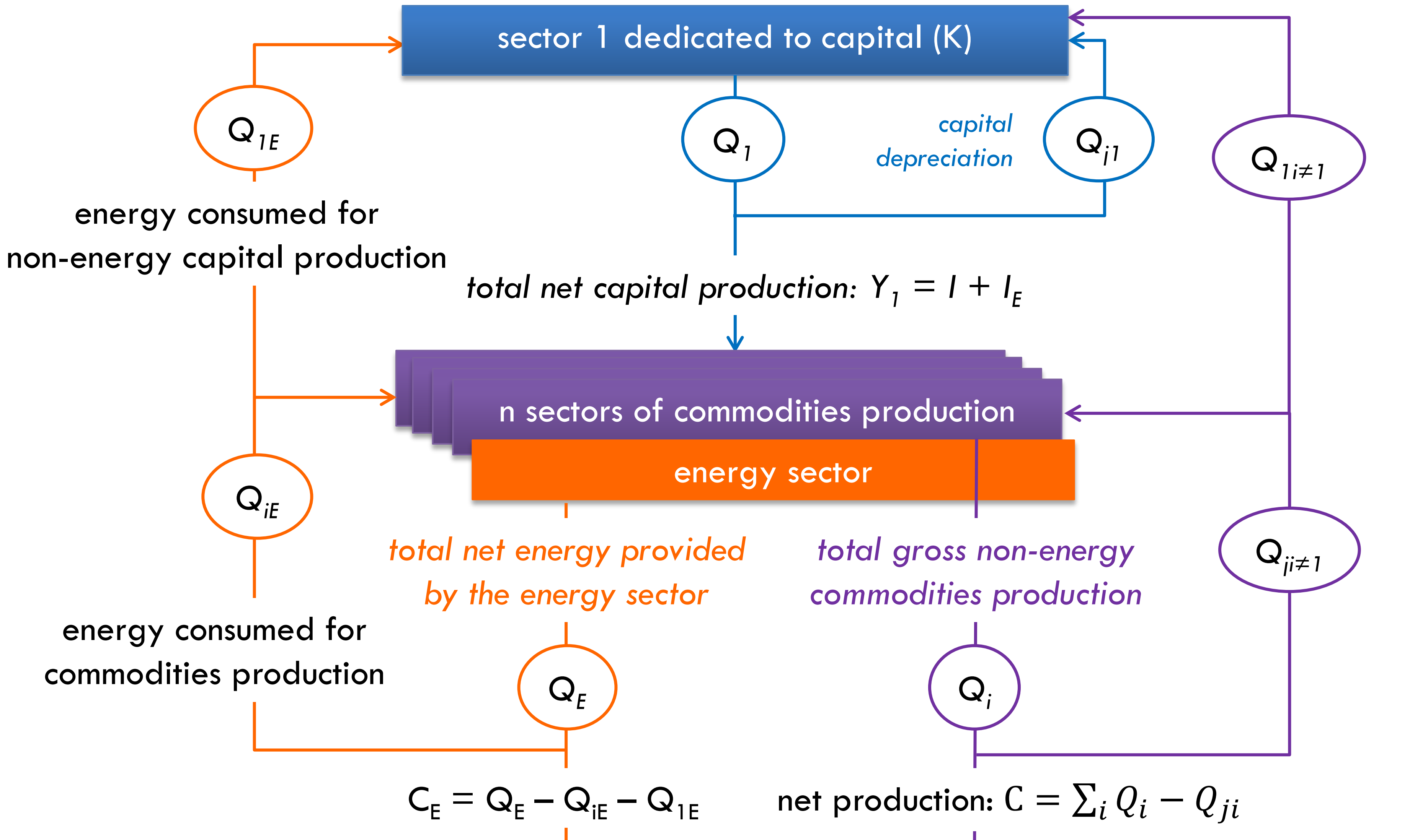
- Comparison of both scenarios (with minimum investment x3)



Perspectives & conclusion 1: Energy part

- Embodied energy is a key point to analyse transition energy scenario
- Huge lack of data on energy intensity of construction materials, on global energy consumed for investment and operation, specially for new technologies
- Build a network of experts to
  - validate the values for all the technologies
  - complete the analysis of embodied energy by including
    - storage of electricity and heat
    - energy grids
    - CCS technologies
    - Installations used by consumers
  - evaluate the realistic uncertainties to make sensitivity calculations
- Necessity to analyze the energy mix and the corresponding embodied energy in the form of the different energy carriers
- Compare different options
  - to store the energy investment to renew facilities
  - on the time of the transition
  - on the life time of facilities
  - …

Perspectives & conclusion 2: Coupling with economic model



$$GDP = \sum_{i=1}^{n} Y_i = I + I_E + C + C_E$$

Model basis

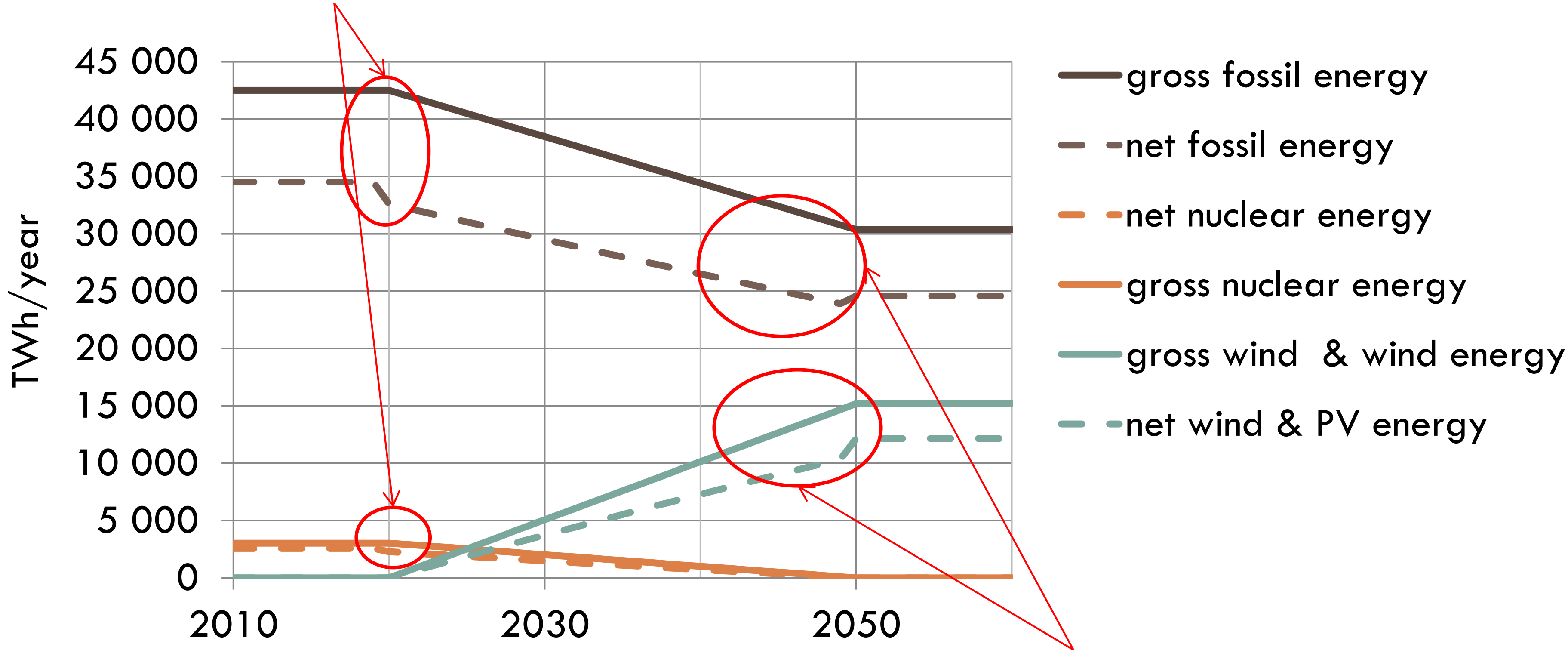
- Economic quantities to describe the dynamic of the production sector
  - Gross production of each sector i: $Q_i = \frac{K_i}{\nu_i}$
    - K_i: capital
    - ν_i: capital productivity
  - ➡ Installations run at full capacity
  - Net profit of each sector: $\Pi_i = Q_i - \left(Q_{ji} + w_i L_i + rD_i\right)$
    - $w_i L_i$: cost labor with the wage function $\frac{\dot{w}}{w} = \phi(\lambda)$ where $\lambda = \frac{L}{N}$ the employment rate
    - D_i: debt with $\dot{D}_i = I_i - \Pi_i$
    - ➡ Investment insured by profits generated by each sector and its bank loan
  - Total investment: $I(t) = \sum_i \alpha_i I = \sum_i \left(\dot{K}_i + \delta' K_i\right) = Q_1(t) = \frac{K_1}{\nu_1}$
    - α_i: distribution function of I among n sectors with $\dot{\alpha}_i = f(r_i)$
    - r_i: capital yield avec $r_i = \frac{\Pi_i}{K_i}$
    - $\delta' K_i$: capital depreciation including damages
  - Net total production: $GDP = \sum_{i=1}^{n} Y_i = Y_1 + \sum_{i=2}^{n} Y_i$
    - Y_1 = I: net capital production
    - $Y_i = Q_i - Q_{ji}$ = C: net production of commodities for household sector

➡ System of non-linear coupled differential equations …

Mecanisms of the modeling / simplified energy transition scenario

- Gross & net total production/ « source – carrier »

The starting of PV and wind deployment
is suported by fossils and nuclear



As wind and PV electricity generation increases, it contributes more and more to their own deployment

➡ net wind and PV electricity ↘

➡ net fossil energy relatively to the gross fossil energy ↗