



3RD INTERNATIONAL CONFERENCE ON SMART ENERGY SYSTEMS AND 4TH GENERATION DISTRICT HEATING

COPENHAGEN, 12–13 SEPTEMBER 2017



AALBORG UNIVERSITY
DENMARK

DE LA RECHERCHE À L'INDUSTRIE



COST-BENEFIT ANALYSIS OF DISTRICT HEATING SYSTEMS USING HEAT FROM NUCLEAR THERMAL PLANTS IN EUROPE



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Background (1)

- Urgent need to decarbonize space & water heating in the residential & tertiary sectors

≈ 29% of EU greenhouse gases (GHG) emissions (IEA, 2014)

- Compromise between GHG emissions and heating cost is important

The correlation between GDP and primary energy consumption is ≈ 40-70% (60% average)
(Safa, 2017; Giraud, 2014)

It is crucial to prioritize least-cost alternatives when decarbonising energy systems

If not, the transition towards sustainable energy systems could negatively affect the GDP growth; which may in turn lead to lower the public acceptance for capitalistic energy projects

Background (2)

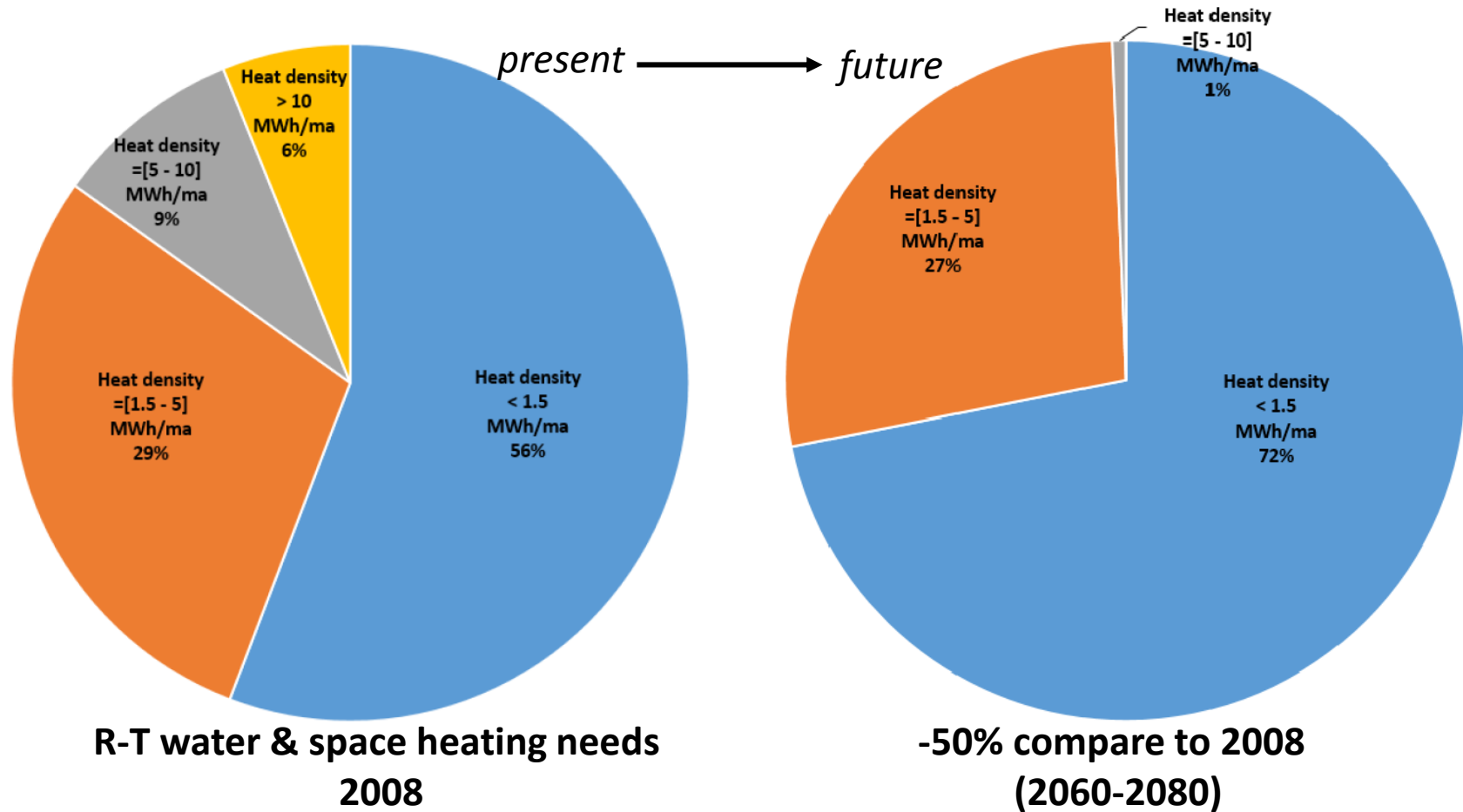
- DH can be competitive, especially in dense urban areas

Threshold in Gils *et al.* (2013): $5 \text{ GWh}_{\text{th}}/\text{km}^2$

Threshold in Persson and Werner (2011): plot ratio > 0.15-0.20

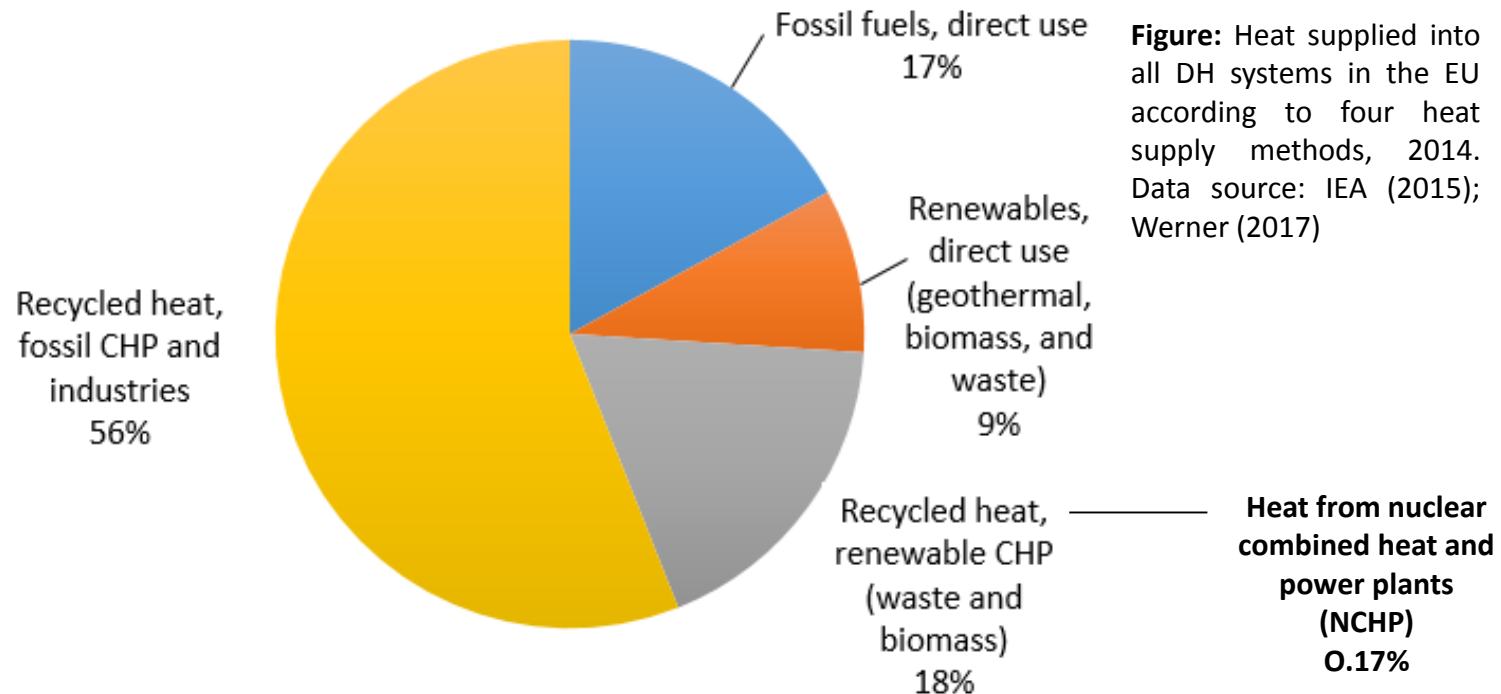
Let's take the example of France with a threshold of $17.5 \text{ GWh}_{\text{th}}/\text{km}^2 \approx 1.5 \text{ MWh}/\text{m.a}$

DH potential in France



Background (3)

- DH has allowed the use of renewable energies and the recycling of heat source that would otherwise be wasted



Interests for DH+NCHP in Europe

Country	Interest for DH+NCHP projects from	Metropolitan area	Plant location	Length of the heat transport line (km)
Czech Republic (CR)	Policy makers, researchers and energy company (CEZ Group)	České Budějovice	Temeline	25
	<i>CR has experienced DH+NCHP systems</i>	Brno	Dukovany	35
Finland	Energy company (Fortum) and researchers	Helsinki	Loviisa	80
France	Researchers	Dunkerque	Gravelines	15
		Lyon	Le Bugey	30
		Paris	Nog.-S.-Seine	90
Hungary	Researchers and energy company (MVM Group)	Paks	Szekszard	30
	<i>Hungary has experienced DH+NCHP systems</i>			
Poland	Policy makers and researchers	Weljherowo	Zarnowiec	18
	<i>Poland does not have nuclear power but is planning for it</i>	Gdynia + Wel.		40
		Gdansk + Gdy.+ Wel.		85
Slovenia	Energy company	Krško	Krško	2.3
		Brežice + Krško		7
UK	Researchers	Bristol	Oldbury	20
		Newcastle	Hartlepool	40
		London	Bradwell	70

Background in a nutshell



- Reducing GHG emissions and prioritizing least-cost solutions is crucial
- DH systems have proved to be in line with these two objectives
- There is unexploited DH potential (DH connexion rate $\approx 7\%$, varying widely)

And there are stakeholders and political wills to exploit it

- There is large amount of wasted heat from nuclear plants

And there are stakeholders and political wills to exploit it

Research questions



- What would be the heat density of DH systems in areas where no DH network is implemented?
- What are the costs and benefits of DH+NCHP systems?
- What are the uncertainties at stake?
- What would be the significant changes between 3rd generation and 4th generation DH technologies?

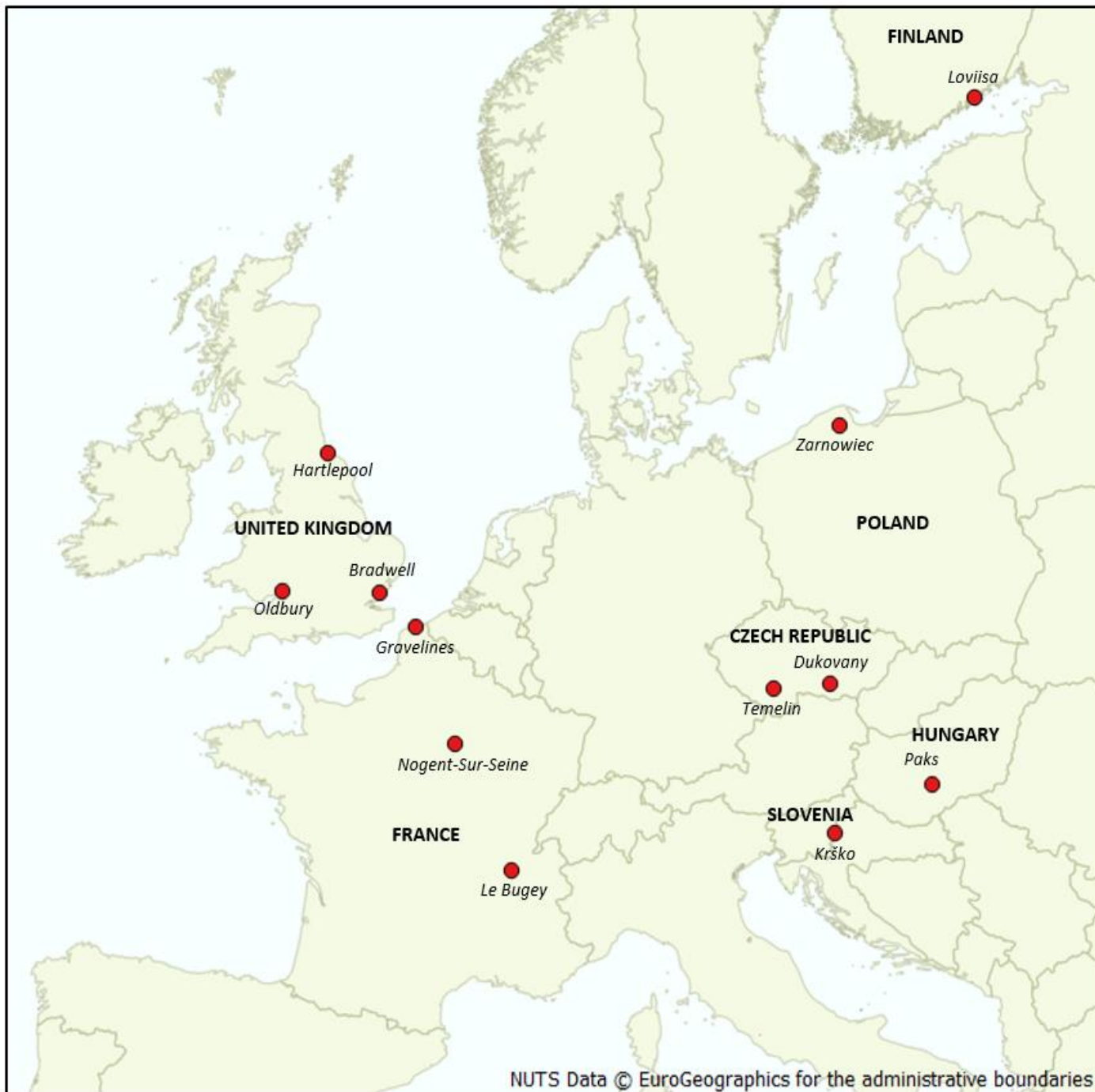


Figure: Spatial mapping of the 12 nuclear sites considered for the CBA of DH+NCHP systems. Nuclear sites are located between 2.3km and 90km from the urban area

Methodology

- Cost-Benefit Analysis (CBA) from the EU public authorities viewpoint (EC, 2014)

EC (2014) recommends to apply:

Discount rate = 3.5%

Technical lifetime = 40 years (longest lifetime of the system components)

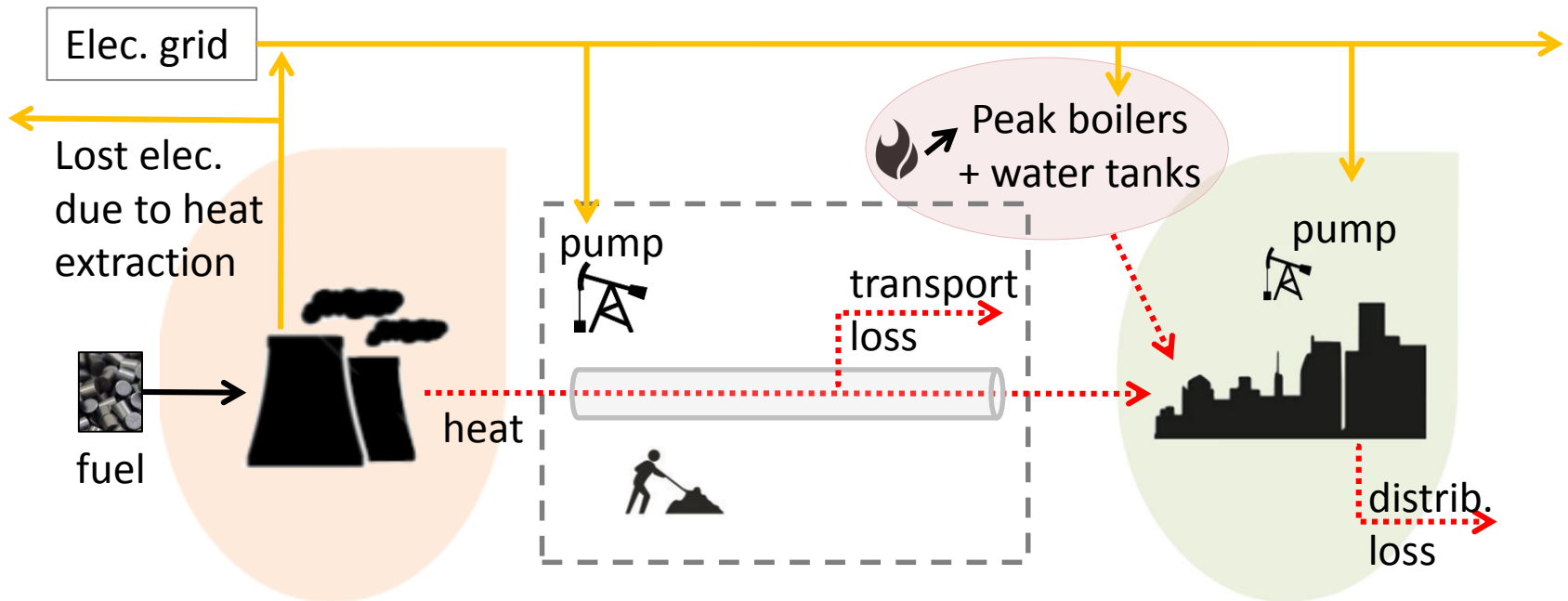
Economic: Levelised cost of the heat (LCOH), Net Present Value (NPV), Payback periods

Environmental: Direct and lifecycle GHG emissions from **operating** DH+NCHP systems

*NB: DH **operational** stages \approx 95% of total GHG emissions (Bartholozzi et al., 2017)*

Both eco and environmental: GHG abatement cost (€/tCO₂)

Techno-economic modelling



How to model the heat distribution network? (1)

- From the effective width to the linear heat density

W, the effective width of a DH network is expressed as:

$$w = A_L / L = 61,8 \cdot a^{-0,15} (m), \text{ where } a = \frac{A_B}{A_L}$$

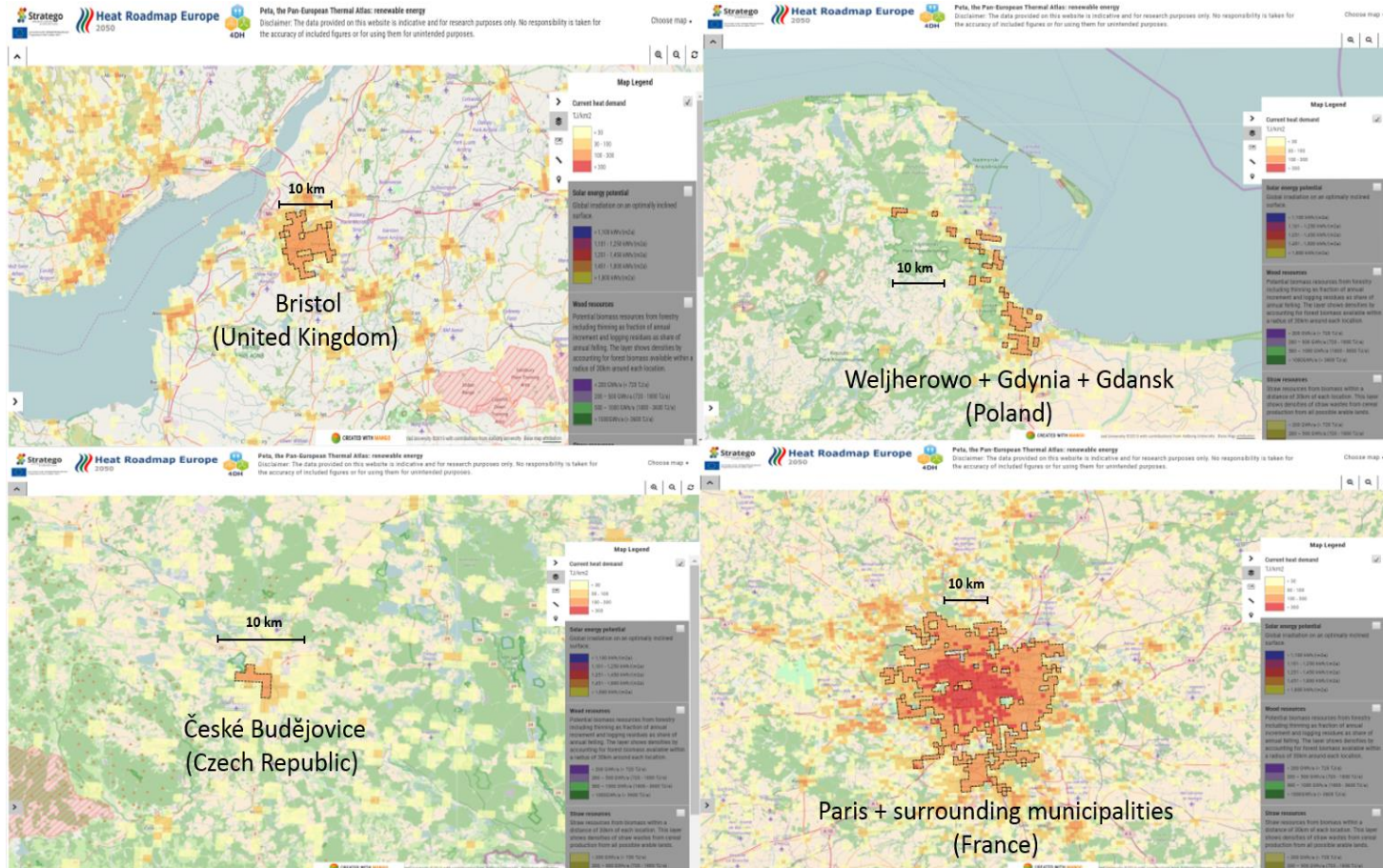
Empirical results from Persson et Werner (2011) based on 83 European networks
In line with Nielsen (2013)

Heat Roadmap Europe (2015) provide the annual space and water heating consumption ($GWh_{th}/km^2 an$) in 2015. We projected it towards 2030 to account for expected decrease in heat demands

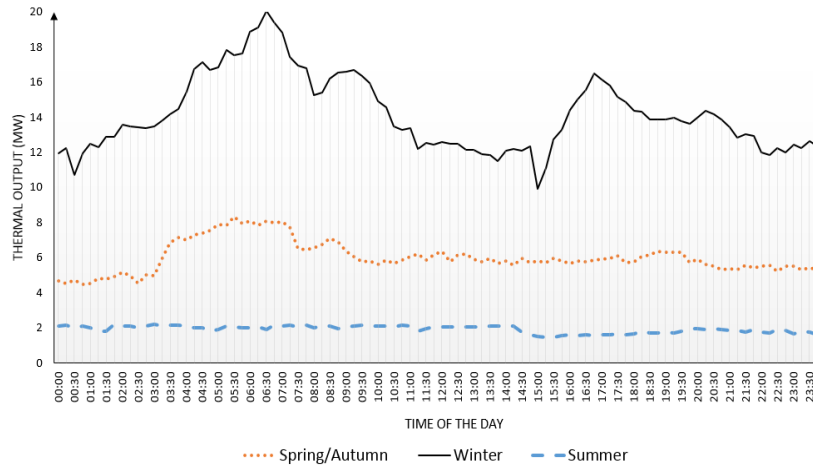
- A_L : Land surface area (m^2)
- A_B : Building surface area (m^2)
- L : DH network length (m)

$$= \frac{\text{Heat consumption of the area (KWh}_{th}/an)}{\text{Av. buildings consumption (KWh}_{th}/m^2 year)}$$

How to model the heat distribution network? (2)



How to model heat generation?



Q_{MAX} (MW), the maximum thermal power required, is calculated in order to be able to supply 80% of the annual heat loads with the NCHP

The remaining 20% are supplied with natural gas heat-only boilers

Capital cost attributable to heat generation with NCHP $\approx 0.1 Q_{MAX}$ (M€)
(see ETI, 2016, for PWR)

Reduction in power generation $\approx 1/6$ of heat extracted (100°C)
(see IAEA, 2016)

How to model heat transportation?

1

G_s (kg/s),
the water flow

$$G_s = \frac{Q_{MAX} 10^6}{C_p \Delta_T}$$

C_p : sp. Water heat cp. (Ws/kgK)
 $\Delta_T = T_{supply} - T_{return}$

2

\dot{v} (m^3/s), the volumetric
flow rate

$$\dot{v} = \frac{G_s}{\rho}$$

ρ : water density (kg/m^3)

3

D (m),
the pipe diameter

$$D = \sqrt{\left(\frac{4 \dot{v}}{\pi v}\right)}$$

v : flow velocity (m/s)
= 3 m/s
(see e.g. Safa, 2012)

4

C_{HTS} (€/m),
the capital cost

$$C_{HTS} = 3000 D^2 + 4000 D + 1500$$

Burried pipelines (see Hirsch et al., 2016; ETI, 2016)

5

P_{PM} (W_e),
the pumping power

$$P_{PM} = \frac{g G_s H}{\eta_p}$$

g : gravitational acc. (m/s^2)
 η_p : pump efficiency ratio (0.75)
 H : lifting height (m), calculated
referring to Darcy–Weisbach

Environmental assumptions

	Direct emissions (t eCO ₂ /GWh _{th}), IPCC (2006)	Lifecycle emissions, EU27 average (t eCO ₂ /GWh _{th}), Ecoinvent (2005)
Biomass	0	0
Fuel oil	264,8	317,2
Natural gas	202,2	221,8
Coal	347,7	385,2
Electricity	Country average	
	Data for 2009 (EEA, 2011) are extrapolated towards 2030 considering that the average GHG intensity of electricity generation will be decreased by 35%, following results from EC (2013; EU average)	

$E_{DH+NCHP}$, specific GHG emissions of DH+NCHP

E_{BAU} , specific GHG emissions generated using conventional heating systems (ref: to ENTRANZE, 2014)

Cm_{GHG} (€/tCO₂),
the marginal GHG
abatement cost

$$Cm_{GHG} = \frac{LCOH \cdot Q_{DH}}{EF_{BAU} - E_{DH+NCHP}}$$

$LCOH$ (€/MWh)
 Q_{DH} : annual DH delivery
(MWh/year)

Results & discussions

- Heat distribution network
- CBA when 25% of dwellings are connected to DH+NCHP systems
- CBA with varying connexion rates
- Sensitivity analysis
- Impact of 4GDH

Heat distribution networks (1)

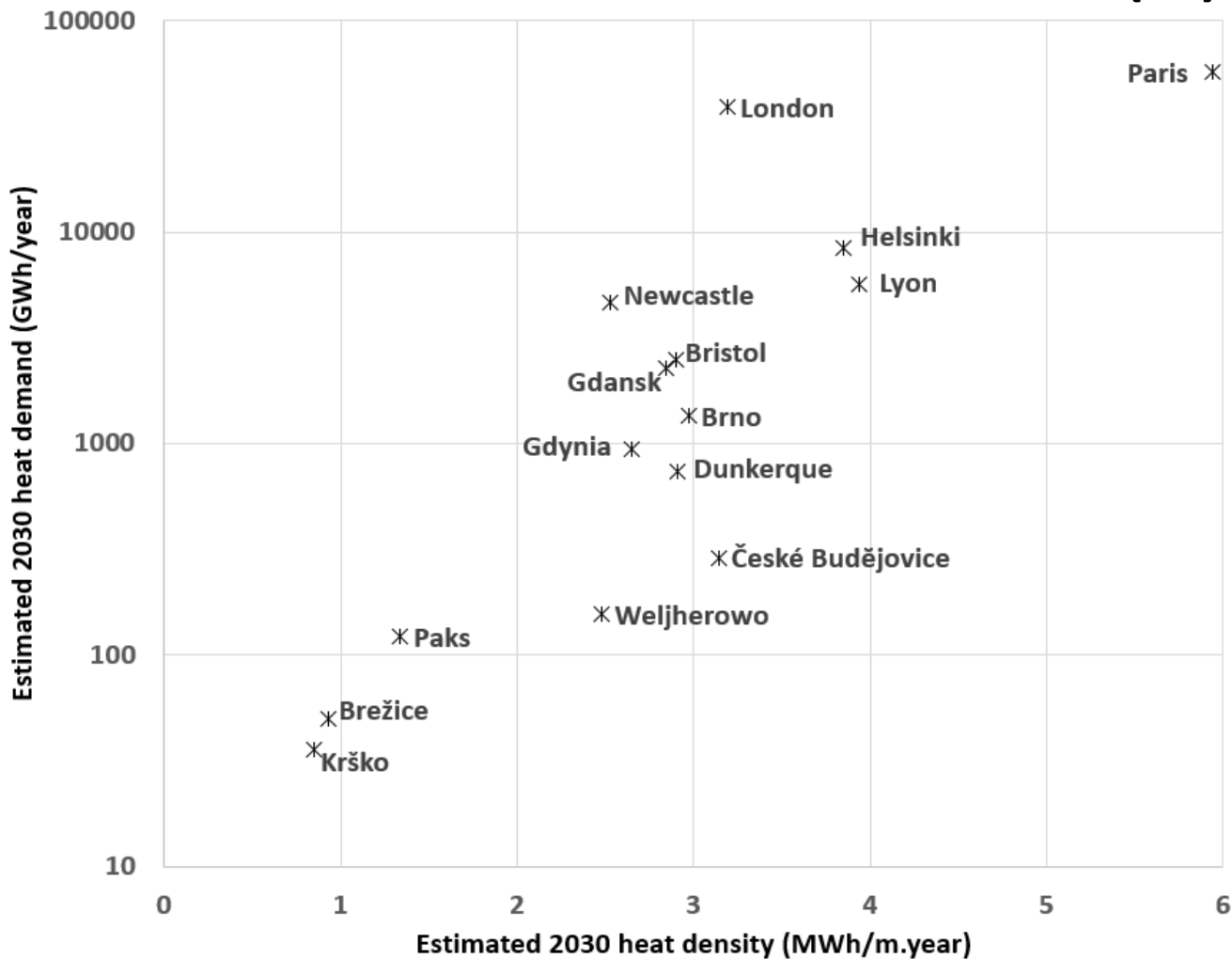


Figure: 2030 heat demand as a function of 2030 heat density

Heat distribution networks (2)

Country	GHG emission factor of space & water heating ($t\ eCO_2/GWh_{th}$), country average	Urban area	Population supplied with the modelled DH network (k capita)	Length of the modelled DH networks (km)	Length of the existing DH networks (km)
Czech Republic	453	České Budějovice	48.3	91.7	101.9
		Brno	167.2	454.4	1349
Finland	288	Helsinki	639.9	2198.2	2750
France	332	Dunkerque	101.9	252.2	34
		Lyon	788.8	1443.3	185.4
		Paris	7913.9	9602.7	1239.9
Hungary	347	Paks	20.5	91.0	85.5
Poland	510	Wieljherowo	31.1	62.9	42
		Gdynia + Wel.	188.3	357.0	331
		Gdansk + Gdynia + Wel.	452.5	800.4	816
Slovenia	256	Krško	6.4	42.4	61.4
		Brežice + Krško	8.9	53.8	78
UK	428	Bristol	241	858.6	10-13 (estimated)
		Newcastle	451	1841.9	18-23 (estimated)
		London	3784	12241.3	400-600 (estimated)

CBA for a 25% discount rate (1)

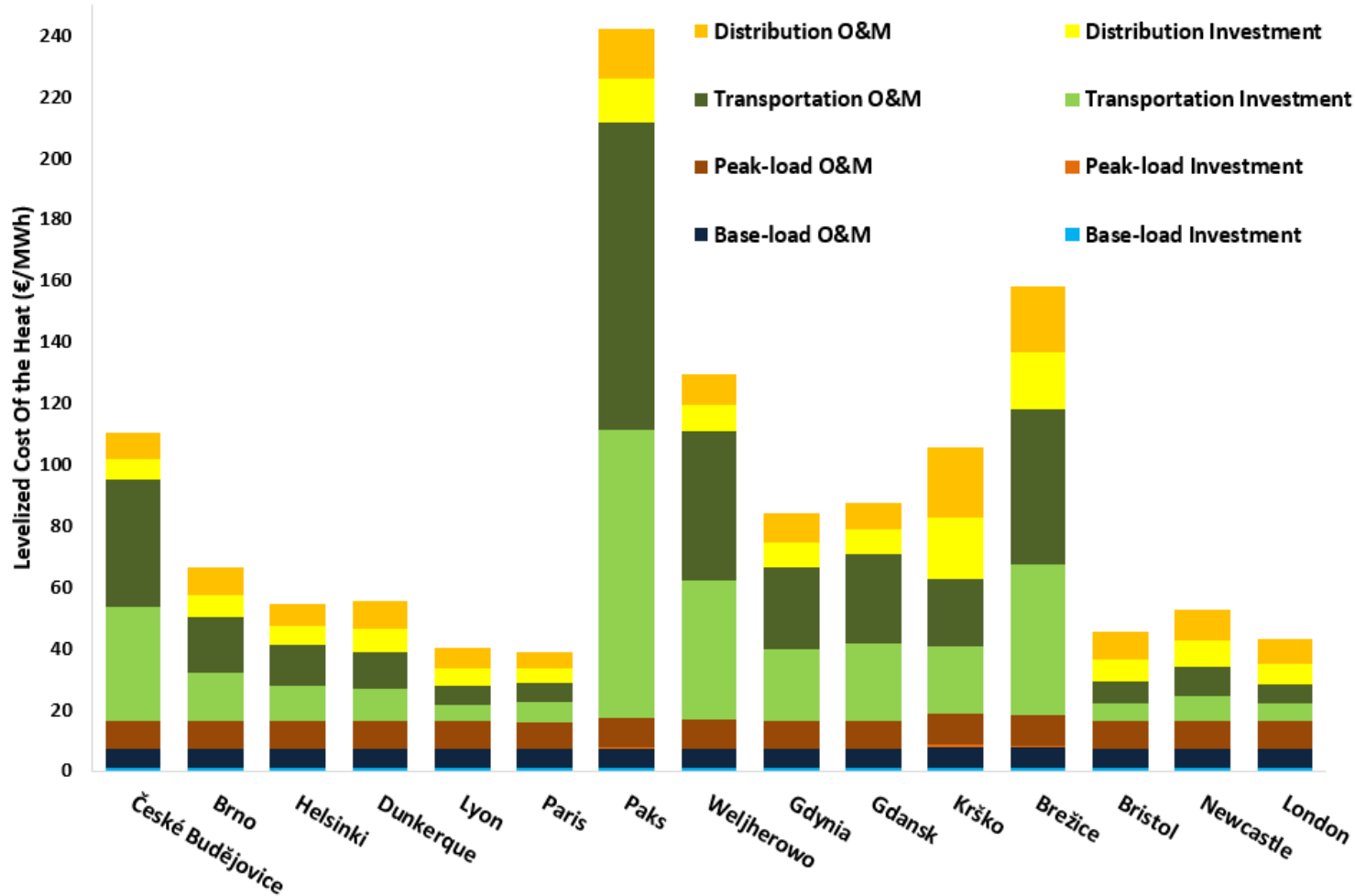


Figure:
LCOH
breakdown

CBA for a 25% discount rate (2)

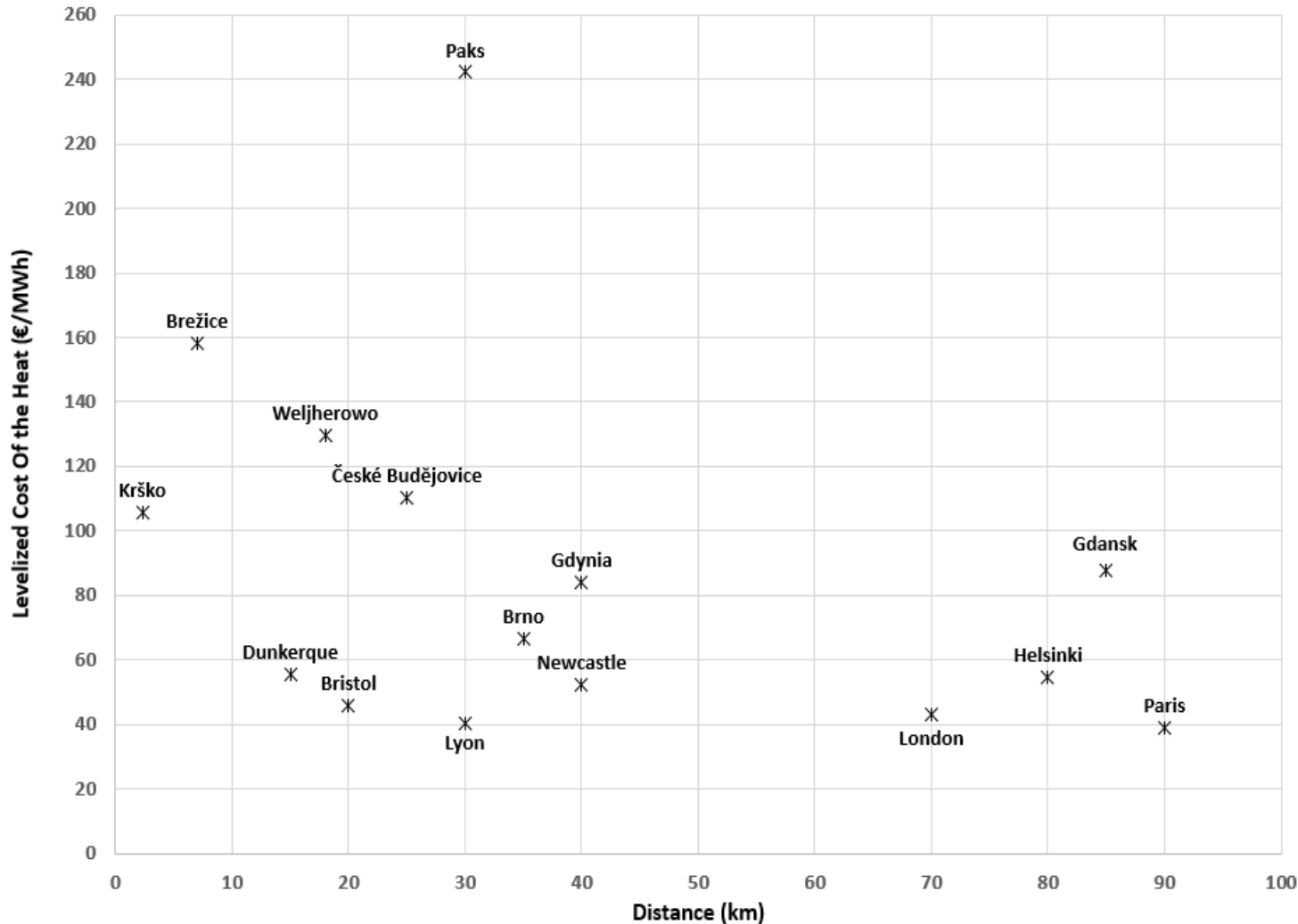


Figure: LCOH as a function of distances from NCHP to cities

CBA with varying connexion rate (1)

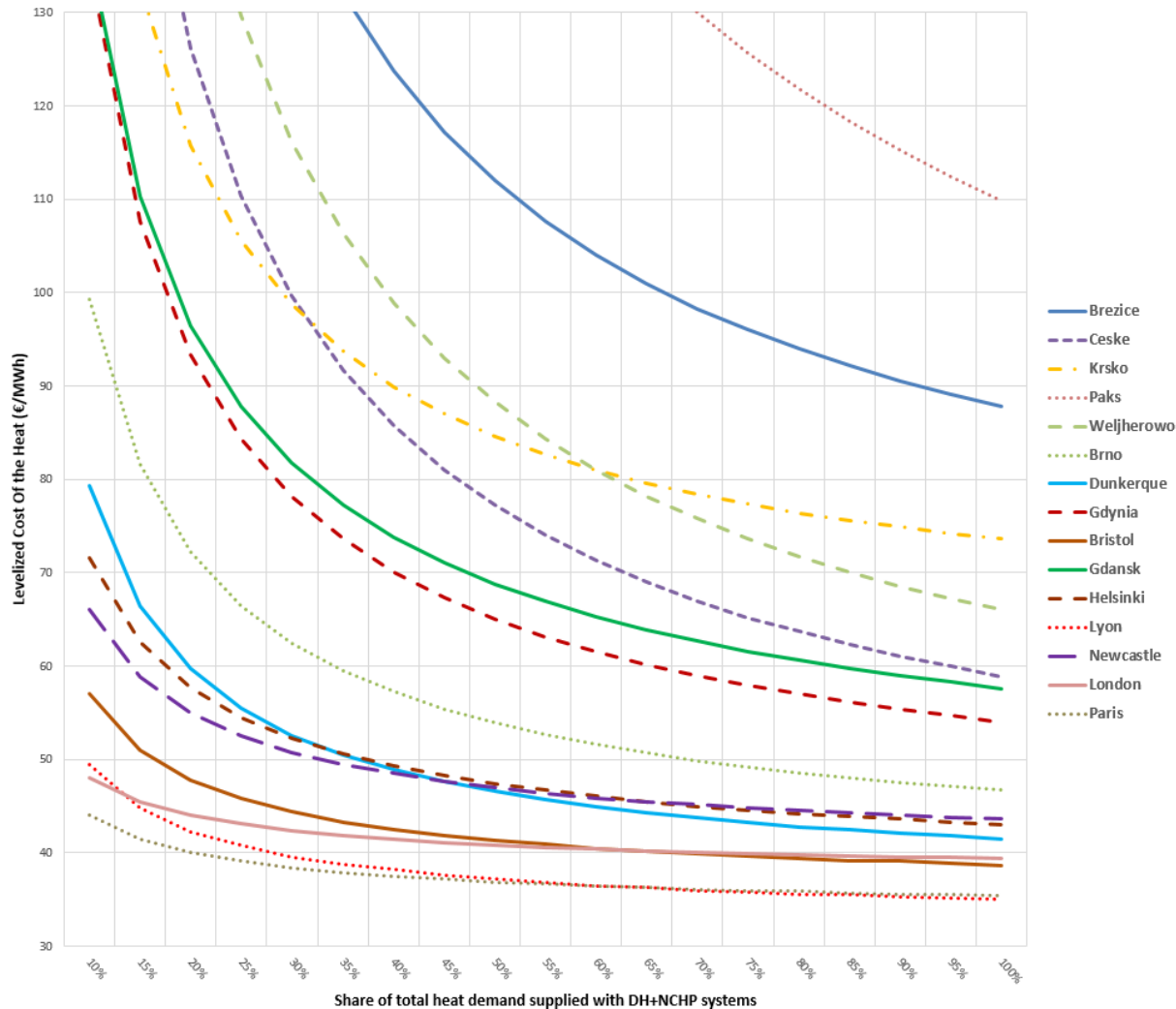


Figure: LCOH with varying DH+NCHP connexion rate



CBA with varying connexion rate (2)

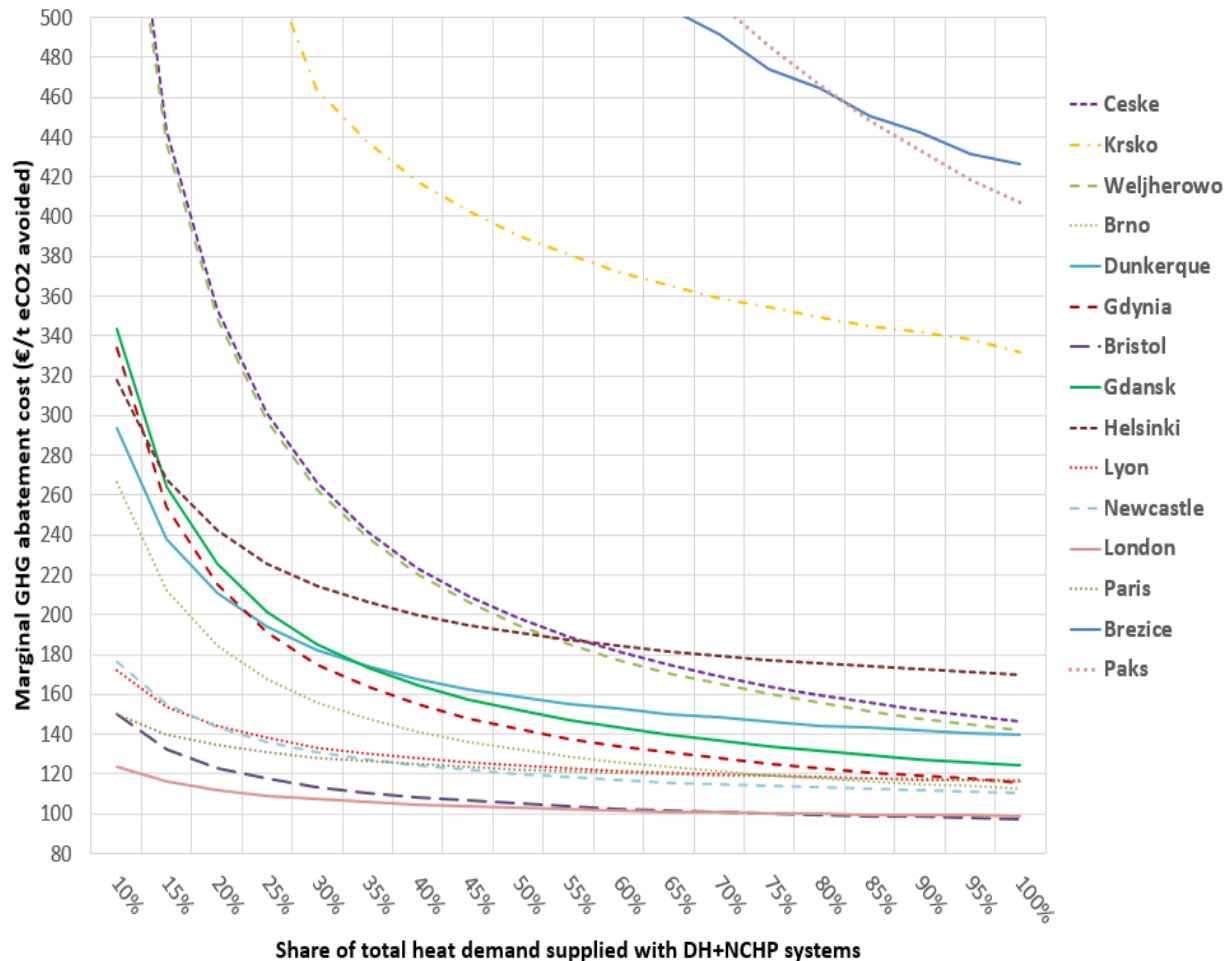


Figure: Marginal GHG abatement cost with varying connexion rate

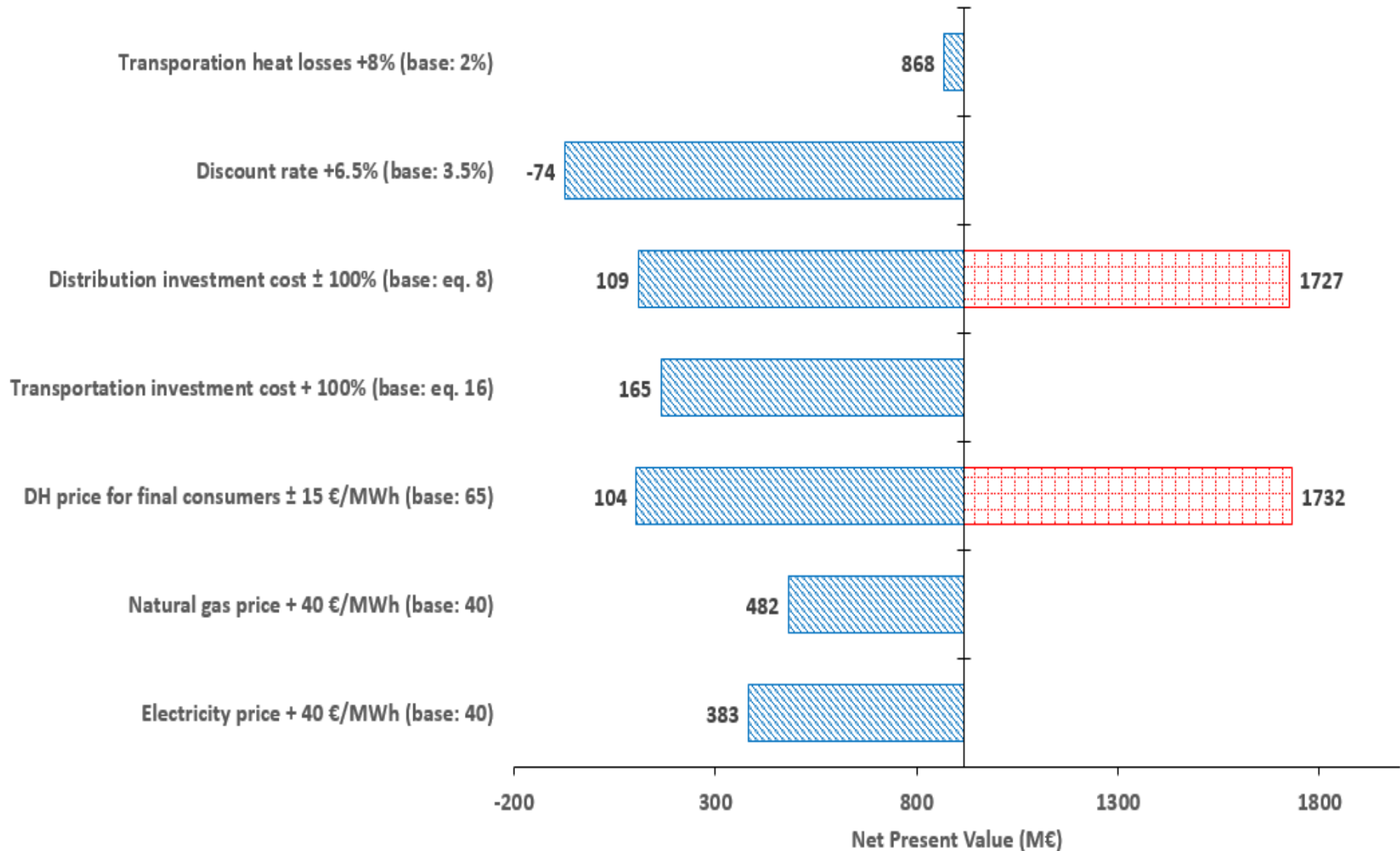
CBA with varying connexion rate (3)

Metropolitan area	NPV profitability threshold (connexion rate from which NPV > 0)	Rankings of payback periods (ascending order)	Rankings of LCOH (ascending order)	Rankings of GHG abatement cost (ascending order)
České Budějovice	75%	6	9	5
Brno	27%	4	6	3
Helsinki	13%	3	5	5
Dunkerque	16%	3	5	4
Lyon	5%	1	2	2
Paris	2%	1	1	2
Paks	NPV < 0	> 40 years	11	7
Weljherowo	NPV < 0	7	9	5
+ Gdynia	51%	4	7	4
+ Gdansk	61%	5	8	4
Krško	NPV < 0	8	9	6
+ Brežice	NPV < 0	> 40 years	10	7
Bristol	7%	2	4	1
Newcastle	11%	3	5	2
London	3%	2	3	1



Sensitivity analysis for the London DH+NCHP system

(25% connexion rate, 10 TWh/yr, 80km heat transportation, DH price = 65 €/MWh)

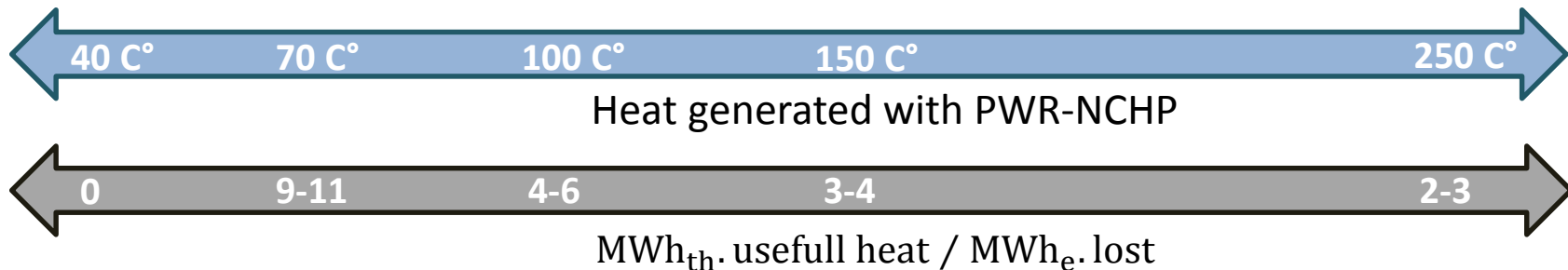


Impact of 4DH Generation

Better insulation of buildings means comfort will be achieved by lower supply temperatures

For NCHP, this means lower electrical losses per unit of heat generated (compare to similar plant producing electricity only)

This accounts for 5-10% of the LCOH for 100°C heat generation



However, other CHP and renewables technologies would also benefit from 4GDH
The competitiveness of NCHP with these sources remain to be studied

Limits & future research

- **Limits of the heat distribution model**
 - Buildings without central heating systems are included
 - Spatial resolution of the data used (GWh/ km²)
 - Neglecting the industrial process heat demand
 - we assumed that the geographic properties of areas with the same heat density level is similar
- **Caution is needed when applying these results**
 - Significant uncertainty is at stake. For implementation in real planning, these results should be checked experimentally in the next step, using parameter values specific to each local context
- **Major stakes for future research**
 - Comparison of DH+NCHP systems with other low carbon heating systems
 - Evaluation of DH+NCHP systems combined with improved buildings performance (4DH context)
 - Stakeholder's interaction and public opinion issues

Conclusions

- There is unexploited DH potential

DH networks with heat density >2.5 MWh/m.a could be deployed so that the total length of DH pipelines would represent approximately 7, 20 and 70 times the length of existing networks in French cities, London and Newcastle/Bristol, respectively

- Cost-effectiveness of DH+NCHP projects is shown in 7 to 11 cases, depending on the connexion rate

For a 25% connexion rate, 7 projects (out of 15) have a positive NPV when the DH price to final consumers is 65 €/MWh

Implementing these projects would reduced GHG emissions by about 10 Mt eCO₂/year

- When considering the marginal GHG abatement cost (€/t eCO₂ avoided), the relative attractiveness of DH+NCHP system is changed

The attractiveness of Polish and Czech DH+NCHP projects is relatively higher.

This is because their heating sector is more dependent on fossil-fuels

A carbon taxation > 50 €/t eCO₂ could be a game changer for DH+NCHP projects

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