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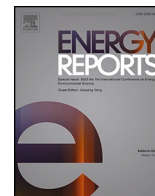
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Research Paper

Impact of decarbonized heating sector at local scale on the national power grid

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ABSTRACT

The space heating sector contributes significantly to global CO₂ emissions due to its heavy reliance on fossil fuels. Electrification is a key strategy for decarbonizing this sector, with a dual impact that must be assessed: a reduction in emissions, at the expense of increased demand on the electricity system during cold periods. Here we focus on how the local electrification of heat, at the scale of a district, impacts the French national electricity system. This question is formulated as a linear programming optimization problem. Results indicate that individual power-to-heat technologies both reduce cost and CO₂ emissions at both local and national scales. When combined with district heating network and thermal energy storages, large-scale heat-pumps enable substantial additional savings. Although electrification increases winter power demand, it does not foster additional needs for gas-fired capacities. We demonstrate that local electrification strategies yield both significant economic and environmental gains at the national level. Specifically, without any incentives on the cost of CO₂ the gains can reach 0.75 tCO₂ per capita per year and 230€ per capita per year.

1. Introduction

The heating of buildings (residential and tertiary sectors) accounts for a substantial portion of country's greenhouse gas emissions (GHG) in Europe. According to the European Environment Agency (EEA, 2023), in 2020, fossil fuels represented 57 % of the energy consumed for household space and water heating, contributing around 35 % of Europe's energy-related GHG emissions. This trend remains true in France, where more than half of the final energy consumed for space heating still depends on fossil fuels, representing 15 % of the country's greenhouse gas emissions (SDES, 2021).

Over the last few decades, renewable energies such as biofuels, thermal solar panels and ambient air from heat pumps have driven most efforts to decarbonize heating, increasing their share of the overall final energy consumption from 16 % in 2000–31 % in 2022 (ODYSSEE-MURE, 2025). However, as biomass reserves are limited and distributed unevenly across Europe, electrification is emerging as a key strategy, driven by gains in energy efficiency and the availability of low-carbon electricity. This approach is supported by European policies such as the EU's 2016 *Heating and Cooling Strategy* (European Commission, 2016), as well as technical assessments like PEPS5 project (ATEE,

2022). Additionally, a 2021 report by the European Joint Research Centre emphasizes that without rapidly phasing out fossil fuel-based heating, Europe is unlikely to achieve its climate mitigation targets. At the French level, a 2023 report from the national transmission system operator RTE (RTE, 2023) supports these findings. Similarly, in the scientific literature studies from the European Joint Research Center or Bloess et al. (2018), Bloess (2019) highlight that heating electrification has great potential, both in terms of reducing CO₂ emissions and providing flexibility.

However, large-scale electrification of heating systems would lead to a sharp rise in electricity demand, with strong seasonal and daily variations. This shift introduces new flexibility challenges, as heating demand peaks often coincide with periods of low intermittent renewable generation. On the other hand, coupling the electricity and heat sectors can also provide flexibility, particularly through the deployment of thermal energy storage (TES). Electrification of heating therefore marks a paradigm shift in energy systems, raising two key research questions:

- i. In which contexts are different heating technologies most relevant (e.g., radiators, heat pumps, individual or district systems, TES)?
- ii. What flexibility can these systems offer to the power grid?

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Nomenclature

Abbreviations

CAPEX	Capital expenditure
CHP	Combined heat and power
DHN	District heating network
DHW	Domestic hot water
OPEX	Operating expenditure
P2H	Power-to-heat
TES	Thermal energy storage

Symbol notation

c_{fixed}	fixed cost in €/kW/year (resp. kg eq. CO ₂ /kW/year) for economic (resp. environmental) cost
$c_{\text{investment}}$	investment costs [€/kW]
$c_{\text{maintenance}}$	maintenance costs [€/kW/year]
c_{var}	variable cost in €/MWh (resp. g eq. CO ₂ /kWh) for economic (resp. environmental) cost
dt	time step [h]
E_{stored}	stored energy [MWh]
$P_{\text{load, curtailment}}$	curtailed power [MW]

$P_{\text{load, district, elec}}$	district power consumption [MW]
$P_{\text{load, national}}$	national power consumption [MW]
$P_{\text{load, P2H}}$	P2H power consumption [MW]
$P_{\text{load, specific/DHW/SH}}$	specific/domestic hot water /space heating consumption [MW]
$P_{\text{in/out, buffer tank/seasonal heat storage}}$	input/output storage power [MW]
$P_{\text{out, base/peak/intermittent}}$	base/peak/intermittent power generation [MW]
$P_{\text{out, CHP, heat/elec}}$	heat/power CHP production [MW]
$P_{\text{out, P2H}}$	P2H thermal production [MW]
$P_{\text{out, individual/collective thermal boilers}}$	individual / collective thermal boilers production [MW]
$P_{\text{out, house/district heating network}}$	house/district heating network thermal production [MW]
$P_{\text{size, base/peak}}$	base/peak sizing power [MW]
$r_{\text{heat/elec/loss}}$	cogeneration production rate [%]
η	efficiency [%]
τ_{life}	lifetime [year]
τ_{loss}	loss rate [%/h]

These issues have been partially explored in previous work. Some studies focus on the sizing and planning of energy systems for heating decarbonization, across different technological options and spatial scales. For instance, the European study from (Pavićević et al., 2020) evaluates the flexibility potential of sector coupling, particularly heat electrification. The analyses of power and heat coupling from (Bloeb et al., 2018; Magni et al., 2022; Zeyen et al., 2021; Zhou et al., 2024) improve the understanding of competition mechanisms between different heat production solutions, also developing a German case study in (Bloess, 2019). Other studies—including (Nagano et al., 2021) in Japan, the PEPS5 report (ATEE, 2022) and in the Ph.D. thesis of A. Clerjon—emphasize the potential of TES in supporting energy system flexibility.

On the other hand, further insights come from studies on flexibility needs only. In the French system. (Clerjon and Perdu, 2019; Heggarty et al., 2019, 2020) have characterized the multi-temporal aspect of the flexibility needs of the French power system. In particular, they underlined those different technological solutions are appropriate to manage flexibility at different time-scales, from hourly to daily and seasonal variations. For example, and at the first order, they show that the seasonal variability of power demand in France and northern European countries is related to heating demand and would be very difficult to manage with electricity storage. As a result, a massive electrification of heating would not only lead to an increase in the daily demand for flexibility, but would also dramatically increase the seasonal need.

We identify two main gaps in this literature. First, while electricity system and its power grid and global, thermal needs are locals. Yet, to our knowledge, no study has assessed how local heating decarbonization strategies affect the operation and sizing of a national power system. Second, while existing studies underline the importance of heat-power synergies and emphasize the potential of TES, they rarely quantify the area of relevance of each technology.

To explore these literature gaps, this study focuses on the French case, where the rate of heating electrification is already more advanced (~17 %) compared to other European countries. This makes France an interesting context to observe emerging trends in heat and power coupled systems.

In this paper, we aim to:

1. Understanding competition mechanisms between various heat production strategies, including individual and collective means, as well

as the integration of thermal energy storage. Those analyses are carried both from the standpoint of the economic cost and global warming potential.

2. Investigating the effects of heating electrification on the national power system: what are the impacts on the load and the potential power production fleet evolution.

The novelty of our work lies in examining how local heat decarbonization strategies impact the national electricity system. While heat production occurs at a local level, electricity can be generated and distributed nationally. Thus, our study focuses specifically on how heat decarbonization strategies at a local scale affect the national power system. To our knowledge, most district-scale studies overlook their impact on the national grid, as illustrated in references (Capone, 2021; Fitó et al., 2022; Morvaj, 2016).

Our approach does not seek to define a national optimal pathway. Rather, it offers insights into how different local heating strategies can shape national outcomes. More broadly, this work contributes to ongoing research on the evolution of energy systems. With growing shares of variable renewable electricity, power systems must become more flexible. Anticipating the impacts of heating electrification is essential to anticipate future energy system design.

1.1. Global scope – framework

This research work models part of the French energy system, using a Linear Programming optimization framework capable of sizing and operating power and heat energy systems. Inputs include hourly time series for electricity demand and variable renewable generation (solar and wind), along with technology cost and performance parameters reflecting existing options in France. While results are specific to the French context, the approach is general and may be applied to other national or regional cases. To our knowledge, this is one of the first studies to evaluate the systemic impact of local heating strategies on the national power system.

2. Method

2.1. General framework

The objective of this work is to assess the impact of different heat

generation strategies – implemented at a *district level* – on the national power system. It aims to provide orders of magnitude and capture the main trends of the coupled energy system. To do so, we seek to reduce the model to a limited number of *key characteristics*, enabling understanding the effects of each technology and parameter (e.g. *cost, efficiency*) on the overall system. We call "key characteristics" the main technical parameters used to describe the general behaviour of energy technologies. These include parameters such as efficiencies, economic costs (CAPEX, OPEX) and CO₂ emissions (fixed and variable). The term *district* denotes a residential locality with a population ranging from a few hundred inhabitants (district) to many thousands (city). However, we warn that the methodology developed is suitable for studying the impact of a district on the national power system, but results do not hold true for a large number of districts. The equations of the case study are developed in section 1.2, illustrated in Fig. 1 and all inputs are details in Tables 1, 2 and 3.

2.2. Case study: structure and equations

This section details the assumptions used to depict the structure of the energy system considered and the corresponding equations employed to formulate the optimization problem. All variables' indexes are given in the nomenclature. The optimization problem seeks to size and design the energy system minimizing its economic costs and CO₂ emissions. Decision variables are sizing powers of each component and powers flows. Constraints correspond to energy balances and operating equations. The model is developed using PuLP (2009), a Python open optimization framework.

2.2.1. Energy system presentation

The energy system considered is represented in Fig. 1. It is composed of two parts, the national one (upper blue part) and the district (lower yellow part) one.

2.2.2. National energy system model

The national energy system is characterized by a single power demand, which is supplied by three types of power production means: *base one* (extremely simplified representation of nuclear power plants), *peak* (perfectly dispatchable gas-fired power plants), and *intermittent* sources (no dispatchable wind power and photovoltaic). Since this work is not focused on the study of the power system, we simplify its representation by not considering hydroelectric plants but only three families of generation mean: base, peak and intermittent. The transmission and distribution power grids are modelled as a copper plate, i.e. the electric power is transmitted without losses.

Base power refers to plants producing power with a constant power $P_{size,base}$. This constant corresponds to the installed capacity, such that

$$\forall t, P_{out,base}(t) = P_{size,base} \tag{1}$$

For *peak plants*, the installed capacity $P_{size,peak}$ is the maximum possible production output at any time, such that

$$\forall t, P_{out,peak}(t) \leq P_{size,peak} \tag{2}$$

Intermittent power corresponds to photovoltaic and wind sources. They are modeled using the 2019 French historical time series, with a time step of one hour. Installed capacities are set equal to those of 2019. For photovoltaics there are 9.4 GW_e installed for an annual production of 33 TWh_e. For wind power, it is 16.5 GW_e installed for an annual production of 102 TWh_e.

Finally, the power generation must equal consumption at any time, and excess power can be curtailed, which gives

$$\forall t, P_{out,base}(t) + P_{out,peak}(t) + P_{out,intermittent}(t) = P_{load,national}(t) + P_{load,district,elec}(t) + P_{load,curtailment}(t) \tag{3}$$

2.2.3. District energy system model

The district has two energy demands, power and heating, reflecting the needs of residential and tertiary sectors.

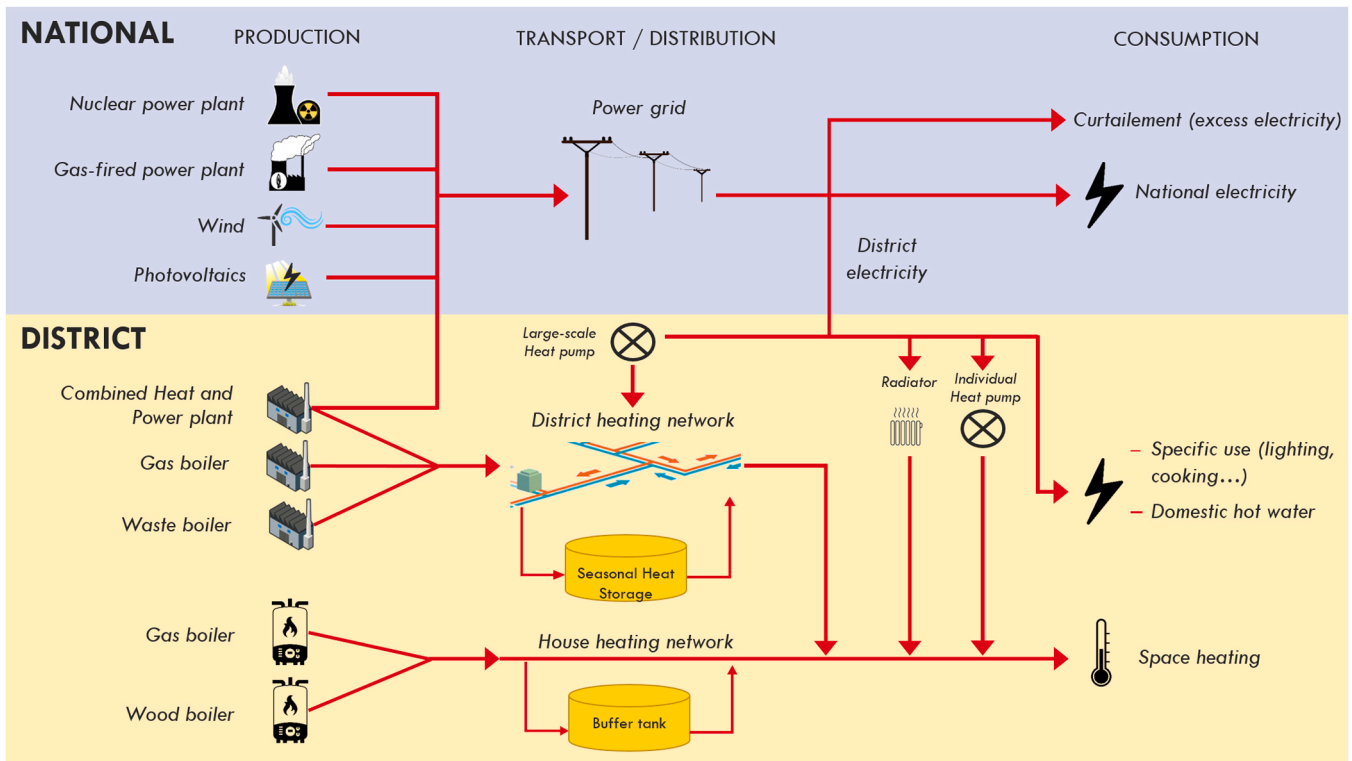


Fig. 1. – Sketch of the energy system considered. The upper blue part in blue represents the French power system. The lower orange part the district energy (power and heat) energy system. The left-hand side shows energy generation means, the right-hand side the various energy loads. The red arrows show the energy flows.

Table 1 Technical, economic and environmental characteristics of the technologies included in the studied power system.

Component	Lifetime (year)	Efficiency (%)	Size limit (MW)	Investment cost (€/kW _e)	Maintenance cost (€/kW _e /year)	Variable cost (€/MWh _e)	Fixed emission factor (kg eq. CO ₂ /kWh _e) ^b	Variable emission factor (g eq. CO ₂ /kWh _e)
Nuclear power	40 (EDF, n.d.)	-	63 130 (max.) (RTE, 2019a)	-	74.09 (Cour des comptes – France, 2021)	29 (Cour des comptes – France, 2014)	345.3 (EcoInvent, 2023)	3 (EDF, n.d.)
Combined cycle gas turbine	25 (Danish Energy Agency, 2023)	65 (EDF, 2023)	-	880 (Danish Energy Agency, 2023)	29.3 (Danish Energy Agency, 2023)	55 (Commission de régulation de l'énergie, 2023)	185.7 (EcoInvent, 2023)	216 (ADEME, 2023)
Wind power	25 (ADEME, 2020)	-	16 494 (fix.) (RTE, 2019a)	1 (ADEME, 2020)	35.3 (ADEME, 2020)	-	920.5 (EcoInvent, 2023)	1.3 (ADEME, 2023), (NREL, 2013)
Photovoltaic	25 (ADEME, 2020)	-	9 435 (fix.) (RTE, 2019a)	943 (ADEME, 2020)	19.4 (ADEME, 2020)	-	66.0 (EcoInvent, 2023)	9 (ADEME, 2023), (NREL, n.d.)
Combined heat and power plant	20 (ADEME, 2020)	$\eta_e = 34\%$, $\eta_{th} = 62\%$	-	1 (AIE, n.d.)	38 (AIE, n.d.)	55 (Commission de régulation de l'énergie, 2023)	373.9 (EcoInvent, 2023)	240 (ADEME, 2023)
Power grid	-	-	-	235	33.24 ^b (Enedis, 2021)	10.4 (Enedis, 2021)	-	1.2 (RTE, 2022)

^a Emission factors are based on calculation from EcoInvent database (version 3.9.1). The quantity selected is climate change IPCC 2021 GWP 100.

^b Expressed in €/dwelling

The power demand includes specific uses as lighting and cooking, domestic hot water and needs for heating from power-to-heat (P2H) technologies, such that

$$\forall t, P_{load,district,elec}(t) = P_{load,specific}(t) + P_{load,DHW}(t) + P_{load,P2H}(t) \quad (4)$$

The heating demand is supplied by two main kinds of heating facilities, thermal heaters or power-to-heat technologies:

- o Thermal boilers are fueled with gas, waste, or wood (only for individual heating).

For the sake of simplicity, we set the ratio between individual wood-fired and gas-fired boilers to be in line with the current distribution in France: namely 33 % wood and 67 % gas, as reported in the national database (Ministère de la transition écologique et de la cohésion des territoires, n.d.). This assumption has however only a small impact on the results, since in our model individual boilers are less competitive than power-to-heat technologies and are therefore not chosen to be installed by our model.

Among large-scale boilers, combined heat and power (CHP) plants deliver both heat to the district and power to the national power grid. Both energy vectors are produced in given proportions r_{heat} and r_{elec} . r_{loss} represents the energy losses of the CHP, such that

$$\frac{P_{out,CHP,heat}(t)}{r_{heat}} = \frac{P_{out,CHP,elec}(t)}{r_{elec}} \quad \text{with } r_{heat} + r_{elec} + r_{loss} = 1 \quad (5)$$

- o Power-to-heat (P2H) corresponds to technologies like electric radiators and heat pumps.

Those heating technologies can be either *individual* or *collective* when connected to a district heating network (DHN). Here also, heat production must meet demand at all time, such that

$$\forall t, P_{out,house\ heating\ network}(t) + P_{out,district\ heating\ network}(t) + P_{out,P2H}(t) = P_{load,SH}(t)$$

$$\text{with } \forall t, P_{out,house\ heating\ network}(t) = P_{out,individual\ thermal\ boilers}(t) + P_{out,buffer\ tank}(t) - P_{in,buffer\ tank}(t)$$

$$\forall t, P_{out,district\ heating\ network}(t) = P_{out,collective\ thermal\ boilers}(t) + P_{out,seasonal\ heat\ storage}(t) - P_{in,seasonal\ heat\ storage}(t)$$

For all energy generation plants, the efficiency η of thermal and power plants is defined as the ratio between the input energy (fuel, power) and the output energy (power or heat), such that $\eta = \frac{P_{out,-}}{P_{in,-}}$.

The technical characteristics of every technology are provided in Table 1, Table 2, and Table 3.

Two kinds of thermal energy storage (TES) are included in the model: long-term and short-term (daily). The long-term storage is model with the technical characteristics and costs of a pit storage and must therefore be connected to a DHN. Short-term storage corresponds to buffer tanks installed in dwellings. Each TES have different thermal losses, referred to as τ_{loss} . The state of charge E_{stored} of each storage decreases of the ration τ_{loss} at every time step, which may be written as

$$\forall t, E_{stored,-}(t + dt) - E_{stored,-}(t) = dt \times (P_{in,-}(t) - P_{out,-}(t) - \tau_{loss,-} E_{stored,-}(t) \text{ with } - \in \{buffer\ tank; seasonal\ heat\ storage\}) \quad (6)$$

2.2.4. Objective function definition

First, based on a mono-objective optimization, calculation is carried on economic (€) and environmental (CO₂) costs independently. Then, we conduct a multi-criteria analysis to evaluate trade-offs between both indicators.

Table 2
Technical, economic and environmental characteristics of the heating facilities included in the model.

Component	Lifetime (year)	Efficiency (%)	Investment cost (€/kW _{th})	Maintenance cost (€/kW _{th} /year)	Variable cost (€/MWh _{th})	Fixed emission factor (kg eq. CO ₂ /kW _{th})	Variable emission factor (g eq. CO ₂ /kWh _{th})							
Large-scale gas boiler	25	(Danish Energy Agency, 2023)	103 ^a	(Danish Energy Agency, 2023)	60	(Danish Energy Agency, 2023)	1.95	(Danish Energy Agency, 2023)	55	(Commission de régulation de l'énergie, 2023)	19.8	(EcoInvent, 2023)	216	(ADEME, 2023)
Waste boiler ^b	-	-	-	-	-	-	-	-	11	(AMORCE, 2019)	-	-	366	(ADEME, 2023)
Individual gas boiler	20	(Danish Energy Agency, 2022)	97	(Danish Energy Agency, 2022)	160	Median	10	Median	55	(Commission de régulation de l'énergie, 2023)	50.5	(EcoInvent, 2023)	216	(ADEME, 2023)
Individual wood boiler	20	(Danish Energy Agency, 2022)	82	(Danish Energy Agency, 2022)	200	Median	25	Median	32	(Ministère de la transition écologique, n.d.)	50.5	(EcoInvent, 2023)	12.3	(ADEME, 2023)
Electric radiator (aluminium, inertia)	10	Median ^c	-	-	400	Median	-	-	-	-	95.3	(EcoInvent, 2023)	-	-
Water radiator (aluminium)	15	Median	-	-	340	Median	-	-	-	-	83.0	(EcoInvent, 2023)	-	-
Individual heat pump	12	(Danish Energy Agency, 2022)	3 ^d	Median	957	Median	19	Median	-	-	168.5	(EcoInvent, 2023)	22.33	(EcoInvent, 2023)
Large-scale heat pump	17	(Danish Energy Agency, 2023)	3.5 ^d	Median	600	Median	27	Median	-	-	-	-	-	-
Individual thermal solar ^e	25	(Danish Energy Agency, 2022)	40	(Danish Energy Agency, 2022)	1000	(ADEME, 2020)	9	(ADEME, 2020)	-	-	383.3	(EcoInvent, 2023)	-	-
Large scale thermal solar ^f	25	(ADEME, 2020)	45	(Danish Energy Agency, 2023)	700	(ADEME, 2020)	3.9	(ADEME, 2020)	-	-	179.5	(EcoInvent, 2023)	-	-
District heating network ^g	20	(ADEME, 2019)	-	-	60	(AMORCE, 2020)	2	(AMORCE, 2020)	400	(AMORCE, 2020)	5.9	(EcoInvent, 2023)	2 418	g eq CO ₂ /m

^a Efficiency based on gross calorific value

^b Fixed size: 100 W_{th}/inhabitant, heat production from waste incineration: 10⁻⁴ MW_{th}/inhabitant, amount of waste: 0.4 t_{waste}/inhabitant (UVE Athanor, Grenoble), fixed CO₂ emissions are considered equal to zero because the boiler is built whether or not there is heat recovery.

^c Medians values provided the tables for costs and technical data are based on various sources including DEA (Danish Energy Agency, 2020, 2022, 2023), IEA(IEA and NEA, 2020) and French experts like ADEME (ADEME, 2020), AMORCE(AMORCE, 2019, 2020), Engie(Engie, 2023) and heating device retailers.

^d For heat pumps, the term *Coefficient Of Performance* is used instead of efficiency. It is calculated as the ratio of thermal energy output to electrical energy input.

^e Expressed in €/m² and g eq. CO₂/m², size limit: 10 m²/dwelling (upper bound from the literature)

^f Expressed in €/m² and g eq. CO₂/m², size limit: 15 000 m²/unit (upper bound from the literature).

^g District heat density considered: 8 MWh/m/year (Average density of DHN in France).

Table 3

Technical, economic and environmental characteristics of the heat storage technologies included in the studied energy system.

Component	Lifetime (year)	Loss rate (%/h)	Maximal size (L/dwelling)	Investment cost (€/kWh _{th})	Fixed emission factor (g eq. CO ₂ /kWh)
Hot water tank	20 (ADEME, 2020),(Engie, 2023)	0.6 (Danish Energy Agency, 2020)	300 (Engie, 2023)	250 Median	40 (EcoInvent, 2023) 626 (EcoInvent, 2023)
Buffer heat storage	10 (France Chauffage Solaire, n.d.)	1.5 (France Chauffage Solaire, n.d.)	900 (Engie, 2023)	164 Median	40 (EcoInvent, 2023) 626 (EcoInvent, 2023)
Seasonal storage ^a	20 (Danish Energy Agency, 2020)	0.08 (Danish Energy Agency, 2020)	-	0.58 (Danish Energy Agency, 2020)	30 (EcoInvent, 2023) 795 (EcoInvent, 2023)

^a We consider in this work a Pit Thermal Energy Storage (PTES) technology.

2.2.4.1. *Mono-objective optimization.* The one-objective function corresponds to the sum of the annual costs of each system component, i.e.

$$Objective\ function = \sum_{components} Annual\ costs \tag{7}$$

Here, the term *cost* refers either to *economic* or *environmental* cost. Annual costs are calculated as the sum of fixed and variable cost without applying any discount rate, such that.

$$Annual\ costs = c_{fixed} \times P_{size,-} + c_{var} \times \frac{1}{\eta_-} \int P_{out,-} dt \tag{8}$$

For *environmental* optimization, cost is expressed in terms of global warming potential (GWP). This measure quantifies the emissions of various greenhouse gases by converting the quantities of the various gases emitted into the equivalent quantity of carbon dioxide with the same GWP, according to the IPCC definition ((IPCC, 2007), part 2.10.1).

The fixed cost refers to CO₂ emissions over the construction and dismantling of the component, while the variable cost reflects greenhouse gas emissions during operation.

In *economic* optimization, the fixed component includes construction and maintenance costs i.e

$$c_{fixed} = \frac{c_{investment}}{\tau_{life}} + c_{maintenance} \tag{9}$$

Here, τ_{life} denotes the lifetime of the component. The variable part refers to operational expenditures over one year, in most cases fuel costs. We consider no discount rate because we are assuming that investments and profits are made at the same time.

2.2.4.2. *Multi-criteria analysis.* The multi-objective optimization integrates economic (€) and environmental (CO₂ eq.) criteria, weighting one over the other (CO₂ eq.) using a penalty coefficient on CO₂:

$$Objective\ function = \sum_{components} Annual\ economic\ costs + CO_2\ penalty \times \sum_{components} Annual\ CO_2\ emissions \tag{10}$$

This approach facilitates the examination of trade-offs between economic and environmental costs. By varying the artificial weight assigned to the CO₂ emissions, Pareto fronts between costs and CO₂ emissions can be plotted.

2.3. *Input data*

This study considers a virtual district comprising 100,000 inhabitants, a population size which allows collective infrastructures to be developed while still being very small compared to the national scale.

The optimization is carried out over one year, with a time step of one hour. All data are based on the year 2019 to avoid disruptions due to the COVID-19 sanitary crisis. Intermittent power generation and national power demand (Fig. 2(a)) are based on time series provided by (RTE, n.d.). District energy demands (Fig. 2(b) for heating part) are based on time-series from RTE and internal sources. For more details, see Appendix A.

The technical, economic and environmental data used in this work are provided in Table 1, Table 2, and Table 3.

3. Results and discussion

3.1. Scenario presentation

To evaluate the decarbonization potential of different heating generation strategies (district scale), we compare five greenfield technological development scenarios, presented in Table 4. Each scenario has distinct and incremental combinations of heating technologies that can be installed by the optimizer.

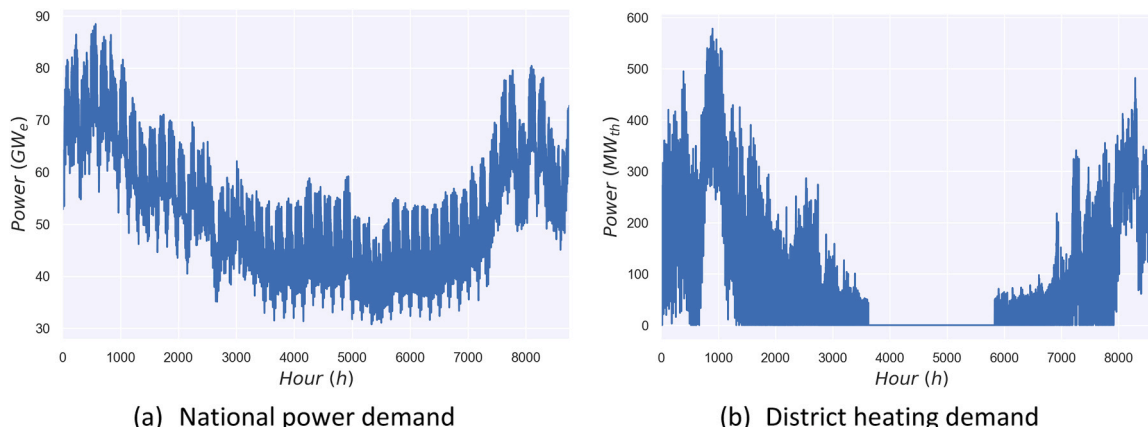


Fig. 2. – Energy demand time series for the year 2019. (a) shows the French power demand, (b) shows the thermal demand of the district considered.

Table 4

Description of the technologies considered in the five scenarios. The left-hand column shows the initial case, which includes the fewest heat generation technologies. Additional technologies are added from left to right. In each scenario, the optimizer installs the cheapest set of technologies to supply heating demand.

Production plants	Individual boilers case	Individual power-to-heat case	District heating case	DH power-to-heat case	Thermal energy storage case
INDIVIDUAL BOILERS					
Individual gas boiler	x	x	x	x	x
Individual wood boiler	x	x	x	x	x
LARGE-SCALE BOILERS					
Large-scale gas boiler			x	x	x
Waste boiler			x	x	x
Combined heat and power plant			x	x	x
POWER-TO-HEAT TECHNOLOGIES					
Electric radiator		x	x	x	x
Individual heat pump		x	x	x	x
Large-scale heat pump				x	x
THERMAL ENERGY STORAGE					
Buffer tank					x
Seasonal storage					x

The initial scenario relies only on *individual boilers* to meet heating needs. The subsequent scenarios—from left to right row—progressively introduce additional heating technologies. First, radiators and individual heat pumps are added (*individual power-to-heat case*). Next, large-scale boilers¹ are incorporated (*district heating case*). Following that, large heat pumps are introduced (*DH power-to-heat case*), which requires the deployment of a DHN. Finally, the last scenario (*thermal energy storage case*) involves thermal energy storage devices at two scales: within the DHN and in individual dwellings.

3.2. Results and discussion outlook

By comparing each technological scenario, we identify the areas in which each technology operates and competes. The results are organized into three parts to address the following key points:

- i. **Global Impact of Local Heating Strategies:** We assess the impact of various heating strategies using two primary metrics: cost in euros and CO₂ emissions. This analysis helps to illuminate the competitive dynamics between different heating solutions, such as thermal boilers versus power-to-heat technologies, and individual versus collective systems.
- ii. **Impact of Local Heating Electrification on the National Power System:** We examine how the large-scale electrification of heating would affect the national power system, with a particular focus on the increased demand for flexibility.
- iii. **Per Capita Impact of Local Heating Choices on the National System:** We quantify how local heating strategies in a district influence the national system. Specifically, we calculate the

reductions in CO₂ emissions and cost savings in euros achieved per inhabitant of the district.

3.2.1. Global impact of local heating strategies

We illustrate the relationships between the cost of the system and its environmental impact using several *Pareto fronts*. These are calculated following the methodology presented in section 1.2 and equation (11). A *Pareto front* is defined as the set of non-dominated solutions, where each objective is considered as equally good. In other words, in a two-variable multi-objective optimization (in this case, € and CO₂), the set of points describes a line beyond which there is no solutions.

Thus, for each case study defined in Table 4, we draw a Pareto front. We can thus compare the evolution of the Pareto front for every added technology to the optimizer ‘toolbox’. Results are shown in Fig. 3. The lower thick black line corresponds to the optimization calculation carried for the national case only, i.e. a case for which district energy demand is set to zero. This curve could be understood as a reference.

As new technologies are available in the ‘technological toolbox’, both the costs and CO₂ emissions of the overall system decrease. Indeed, as shown by the dotted lines, each time a new technology is added (from Individual boilers to Thermal Energy Storage case study), the point moves to the left (lower cost) and to the bottom (lower CO₂ emissions). It underlines that coupling power and heat vectors reduces both economic and environmental costs.

Fig. 3 shows individual P2H has a big impact on both economic and environmental costs (dark blue curve). The introduction of a DHN (light blue curve), collective P2H (orange curve) and TES (yellow curve) slightly strengthens those positive impacts.

Nevertheless, this representation does not enable to understand which technologies are deployed for each case study, i.e. which technologies enable these reductions. To better understand, we present in Fig. 4 the breakdown of the district’s thermal energy supply by technology. The calculations are carried out for the five case studies, each time according to economic (€, left-hand bars) or environmental (CO₂, right-hand bars) criteria.

The analysis of Fig. 4 begins with the individual boilers case (left bars set), where heating is only produced with individual boilers. Moving from left to right, additional technologies can be selected by the solver. This figure highlights the following competition mechanisms between each heating technology and strategy:

- Firstly, power-to-heat technologies are favored over fossil-based counterparts (*Indiv. P2H case (resp. DH P2H case) compared to Indiv. boilers case (resp. DH case)*). This inclination towards P2H technologies becomes even more pronounced with CO₂ optimization, where only a small capacity of individual boilers remains to meet peak demand.
- Next, collective heating (large boilers, CHP, large heat pumps) are preferred over individual ones (*DH case and DH P2H case compared to Indiv. boilers case and Indiv. P2H case*). There is a notable exception observed for the radiator use, which keeps appearing in the heating mix, especially in CO₂ optimization. This result is highly dependent on the cost and emissions assumptions made. In our model, the economic and environmental investment costs of a radiator are 3 times lower than those of a heat pump. In operation, heat pumps are more profitable in the Euro-optimization because of their high coefficient of performance. In CO₂-optimization, taking into account refrigerant leakage leads to a higher variable emission factor. There is however a significant uncertainty in both costs and emissions that could impact the results. Parametric analyses, not presented here to lighten the article, have shown that the ratio radiator/heat pump is very sensitive to the cost used (resp. emissions factor). Nevertheless, the ratio between boilers and P2H technologies remains similar.
- Finally, the incorporation of thermal energy storages leads to a reduction of fossil usage in the economic optimization. In the CO₂

¹ We call *large-scale boilers* those with a thermal capacity greater than 50 kW.

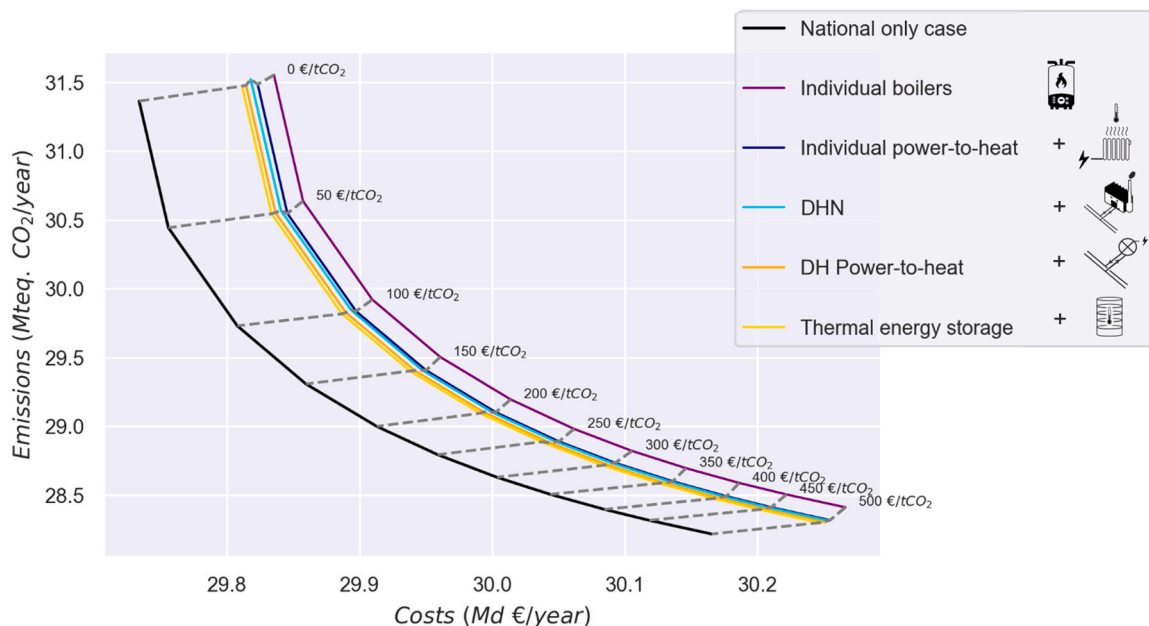


Fig. 3. Pareto fronts calculated for the five scenarios of Table 4. The calculation is performed for national energy system and a zoom is made to grasp the impact of the district heating strategy. The purple curve (top line) corresponds to the case without P2H technologies, i.e. when heat demand is met by individual boilers alone. The dark blue curve refers to the case with individual P2H technologies, the light blue curve corresponds to the case with DH technologies, the orange curve refers to the case introducing P2H technologies at DH scale and the lower yellow curve corresponds to the TES case. The black curve (the lowest) corresponds to the optimization of the national system i.e. a case for which district energy demand is set to zero. The dotted lines link the case studies for which the calculation was performed with the same CO₂ penalty (€/t_{CO2}), ranging from 0 to 500€/t_{CO2}.

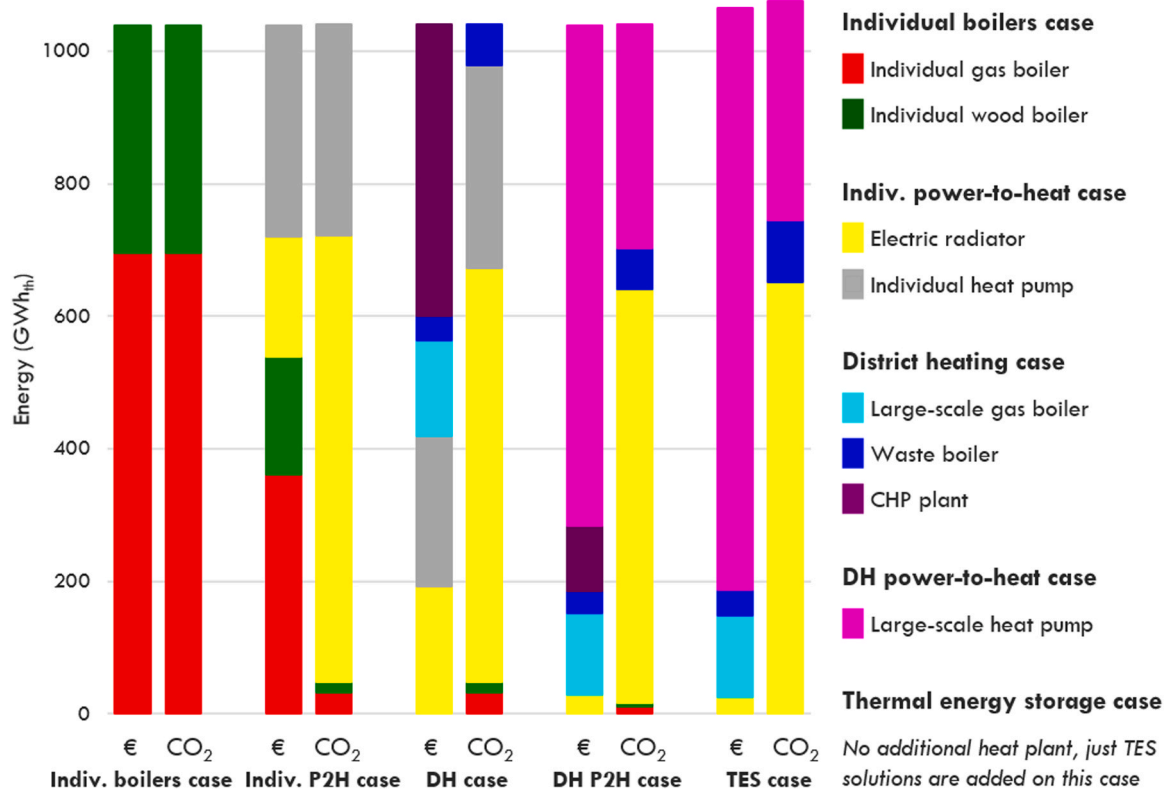


Fig. 4. Heat production mix for the five case studies under each optimization criterion: economic (€) and environmental (CO₂).

optimization, fossils are fully removed (*TES case compared to all other cases*). Indeed, heat production from P2H technologies is favored during low energy demand periods. TES are then charged so that they can deliver energy during peak periods. In this way, TES provide

flexibility that reduces the need for dispatchable fossil thermal boilers.

In summary, these results show that both costs and emissions are

reduced by integrating power-to-heat technologies to replace part of the collective thermal boilers, themselves favored over individual boilers. The integration of thermal storage enables a greater penetration of P2H technologies adding flexibility to the system.

Based on our hypothesis, we have shown that electrifying heating systems can reduce both costs and CO₂ emissions. In the next section, we investigate the impact of a local heating electrification on power flexibility.

3.2.2. Impact of local heating electrification on national power system

We compare here the district's power demand for each of the scenarios. Fig. 5 presents the results both for of economic (full lines) and environmental (dashed lines) optimization. To enhance the readability, the load curves are smoothed with 14 days sliding average.

Fig. 5 shows that the increase in power consumption is not evenly distributed throughout the year. In fact, power consumption rises in winter, during the heating season, as power-to-heat technologies are used. This growth increases the seasonal bump in consumption, and thus the need for seasonal flexibility in the power system. Note that P2H technologies also foster short-term variability when compared with the individual boilers case (purple lines). We remind that there is a significant uncertainty on data assumptions. In this way, the strong seasonal variability observed in P2H cases is expected to be mitigated thanks to the improvements of refrigerant GWP and their leakage. Indeed, reduce refrigerant leakage in heat pumps would rise their share in the heating mix, decreasing radiators one, leading to electricity consumption savings thanks to the high heat pumps efficiency.

Analysis of the results shows that electrification of the heating system leads to an increase in winter consumption, and therefore in the seasonal flexibility need. This might increase the use of dispatchable power plants. However, we observe no rise in gas-fired plant installed along with a reduction of the global gas consumption (See Supplementary information). This means that the district electrification does not increase the need for additional flexible means at the national scale (here, gas fired power plants) and decreases the global CO₂ content of the coupled energy system considered through gas consumption savings. A more detailed analysis of the evolution of flexible means installed would be too extensive to be develop here.

After examining the impact of heating strategies on the entire system, we will look at the gains achieved per capita to understand to which extent those strategies are cost-effective.

3.2.3. Per capita impact of local heating choices on the national system

To precisely quantify the impact of each heating strategy on the national system, we detail the Pareto fronts presented in Fig. 3. Indeed, since the district considered remains small with respect to the country the axes values (€ and CO₂) vary little, leading to difficulties for the interpretation. To better grasp and evaluate the gains enabled by each strategy, in relation to the district inhabitants, the contribution of the national power system (black line) is "subtracted" from each scenario and for each CO₂ penalty value. The result is then divided by the number of the district's inhabitants to reveal the impact of heating one inhabitant for one year. Shown in Fig. 6, each scenario is represented by a cluster of markers where each point corresponds to a calculation performed for a given CO₂ penalty, specified with the upper color bar.

Fig. 6 shows that the electrification of heating enables to save at least 75 € and 0.2 tCO₂ per capita and per year, when compared to the initial case including only individual thermal boilers (grey dotted lines). Little additional savings are made when a connection with a DHN based on thermal boilers is possible (star markers). However, when collective

heat pumps are available (hexagonal markers), it enables additional gains; which are even more reinforced with thermal energy storage (diamond markers).²

Therefore, Fig. 6 shows that, whatever the CO₂ penalty, the integration of P2H and TES leads to a cheaper and lower-emitting system. This means that, whatever the financial incentives for reducing CO₂ emissions, electrification (i.e., the development of P2H means) is the optimal solution. P2H is a no-regrets technological choice that can already be made.

Finally, the significant gap between individual boilers and P2H solutions could explain why radiators would be mostly preferred to conventional boilers in some countries.

3.3. General discussion

This study quantifies how local heating choices affect a simplified national power system. Across all optimization runs, introducing power-to-heat technologies reduces total annual cost and life-cycle GHG emissions. District-scale heat pumps coupled with thermal energy storage strengthen these effects by shifting heat production to hours with low marginal cost and low carbon intensity. Indeed, district heating and TES enable off-peak electricity consumption, reducing operation during high-carbon hours.

Electrification also increases winter electricity consumption, but this does not require additional gas-fired capacity at the national level. Total gas use declines because direct combustion for heat is replaced by electricity-driven heat production (Appendix B). Part of the additional flexibility need is supplied by thermal energy storage and by the ability of heat pumps to shift operation within the day.

These results are consistent with recent European studies on sector coupling that report cost and emission benefits from electrified heat and storage. Studies of the German and European contexts show that electrified heat combined with thermal energy storage reduces total system cost and carbon-dioxide emissions while helping integrate wind and solar (Bloess, 2019; Bloess et al., 2018). Model linking of the European power and heating sectors also reports cost-effective emission reductions when electricity is low-carbon (Kavvadias et al., 2019; Pavičević et al., 2020). At the district scale, an analysis of a Nordic system finds that thermal energy storage and participation in reserve markets mitigate cost risks while electrified heat reduces emissions (Sihvonen et al., 2024). At the regional scale, a least-cost pathway for Northern-central Europe shows that sector coupling increases electricity demand and heat storage while reducing costs and emissions, with investments in electric heat supply playing a central role (Gea-Bermúdez et al., 2021). These patterns are consistent with the Heat Roadmap Europe studies (Paardekooper et al., 2018), which identify system-wide cost and emission benefits from expanding district heating, large heat pumps, and storage.

The present analysis is consistent with this body of work and adds two elements. First, it quantifies how a single district-scale decision propagates to national-scale outcomes. Second, it reports per-capita effects and shows that winter load increases do not require additional gas-fired capacity under the tested assumptions, while total gas use declines. These two contributions clarify where electrified heat and storage deliver system-level benefits and how those benefits appear at the national scale under French conditions.

4. Limits of the methodology and further works

The model is intentionally a simplified representation of the French

² For reference, CO₂ content in France for heating is around 1.8 t CO₂ eq./cap/year. (Heat CO₂ content in 2022: 0.181 kg CO₂ eq./kWh (ADEME, 2023; Carbone 4 2022; FEDENE, 2023), French population in 2020: 67.4 million (INSEE n.d.), French heat consumption in 2020: 669 TWh (Carbone 4 2022))

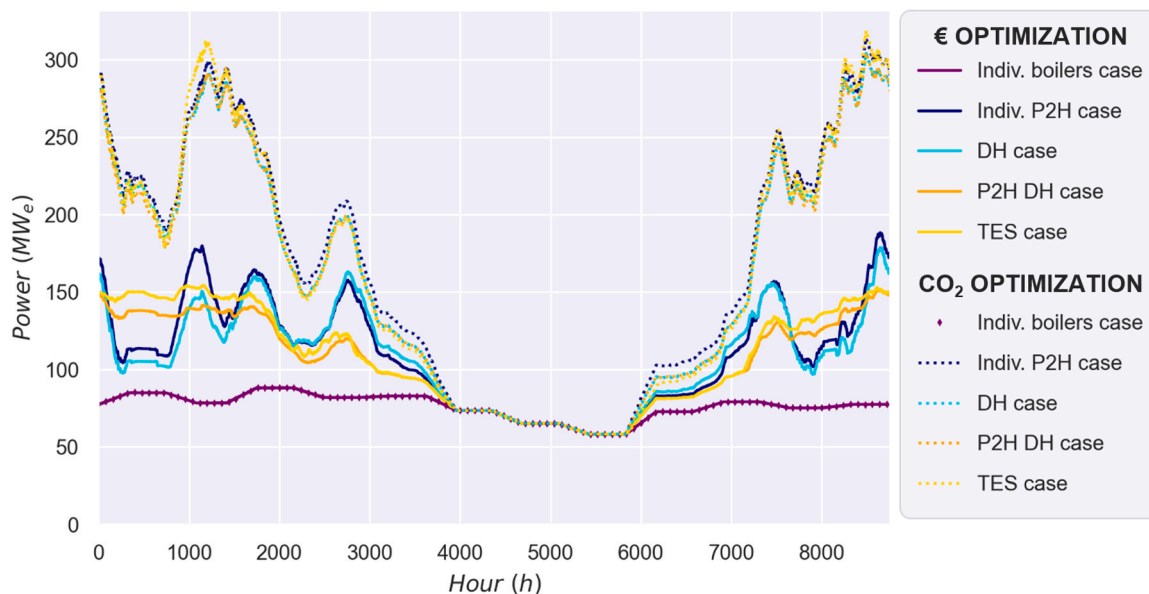


Fig. 5. – Load curves of the district for the five case studies under each optimization criterion.

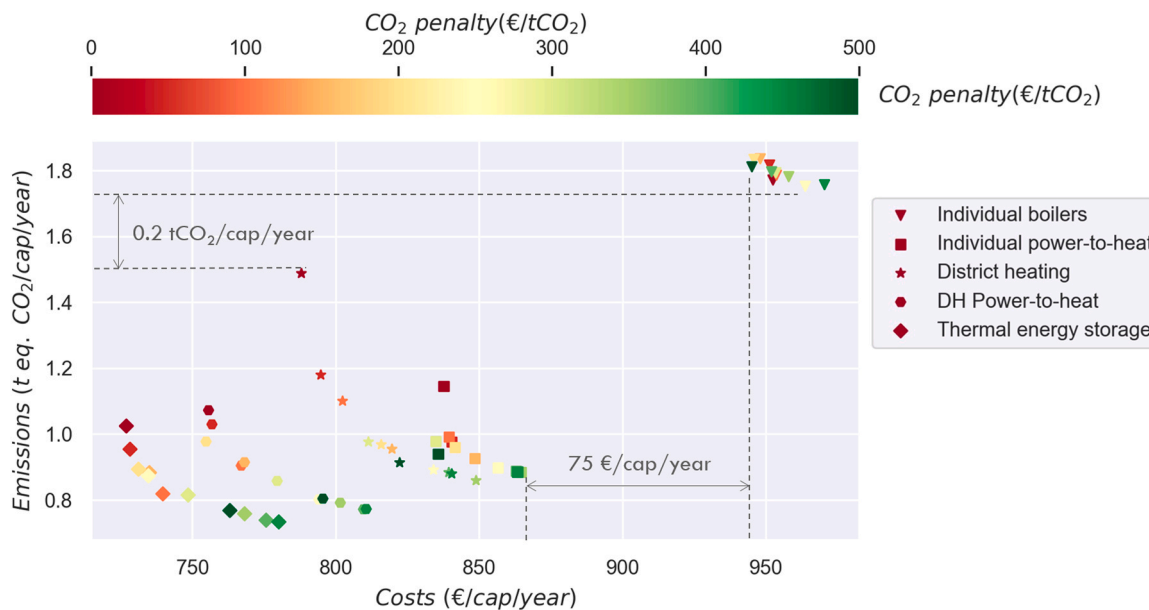


Fig. 6. Normalized Pareto fronts per capita for the five case studies, derived from Fig. 3. As the color of the marker evolves from red to green, the CO₂ penalty increases. Each marker refers to a scenario.

energy system, designed to capture system-level trends and mechanisms. The primary objective of this work is to assess the synergies between heat and electricity energy carriers. To keep the analysis transparent and understandable, the total number of parameters is limited enabling to examine closely the influence of each one on the whole system. The study reflects a simplified French energy system, and the results should be interpreted accordingly. But the methodology is generic and can be applied to other countries by modifying the input data. As such, it is essential to acknowledge the limitations inherent to this approach.

The technical representation of the models is a point that could be further refined to better assess the behavior and integration of technologies. In particular, the national electricity supply is represented as a single node without transmission constraints and without complex unit-commitment features. Nuclear generation is treated as a fixed base component, while gas-fired generation is assumed fully dispatchable.

Several common technologies are absent from the core runs, including hydropower, biomass boilers, and geothermal sources. These choices simplify interpretation but restrict realism.

The representation of heating is also simplified. Technology groups are aggregated; temperature levels in district heating networks are not modelled explicitly; temperature-dependent performance, building thermal inertia, and network losses are not represented. Consequently, the results capture directions but not operational details.

The results reflect the marginal effect of electrifying a single district of about 100,000 inhabitants within a simplified national power system. This district represents a very small share of national energy use; therefore, the conclusions apply to limited, local adoption and should not be extrapolated to a nationwide heating electrification. To overcome this limitation, a countrywide assessment of cost end GHG emissions of heating strategies would be required, taking into account the territorial

specificities of French districts—heating demand, urban density, etc.,—and evaluates decisions across all regions to capture system feedbacks.

Some of those limits are subject to ongoing work.

5. Conclusion

The methodology presented enables to grasp the main implications of coupling local heating production (district or city scale) with the national power grid. Applied to a case study that depicts—in a simplified way—the main characteristics of the French energy system, this work highlights the following key findings:

- Electrification both decarbonizes and reduces cost of heating. On a district scale, a power-to-heat heating strategy without any incentive to reduce CO₂ emissions will always emit 0.5 ton less (on a lifecycle basis) per inhabitant per year than heating strategies based on fossil boilers.
- Collective P2H and TES enable additional savings. In this study, collective means are favored over individual ones. Furthermore, district heating networks enable more efficient large heat pump, and thermal energy storage systems, providing additional flexibility and enabling greater P2H penetration.
- Electrification increases power consumption variability without the requirement to install additional gas-fired plants. In addition, the electrification of heating enables to reduce the global CO₂ content of the energy system.

- Heating strategies at district level have a significant impact at national scale.

CRedit authorship contribution statement

Anne-Geneviève Lemelle: Writing – original draft, Methodology, Formal analysis. **Arthur Clerjon:** Writing – review & editing, Validation, Supervision, Formal analysis, Conceptualization. **Fabien Perdu:** Validation, Formal analysis, Conceptualization. **Philippe Azais:** Validation, Formal analysis, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. District energy demand – Time series construction

This appendix explains how time series for district energy demand are built. Figure 7 gives an overview of the steps followed to edit each load profile, starting from three main time series: the national daily power consumption, a district heating load and an individual domestic hot water load profile.

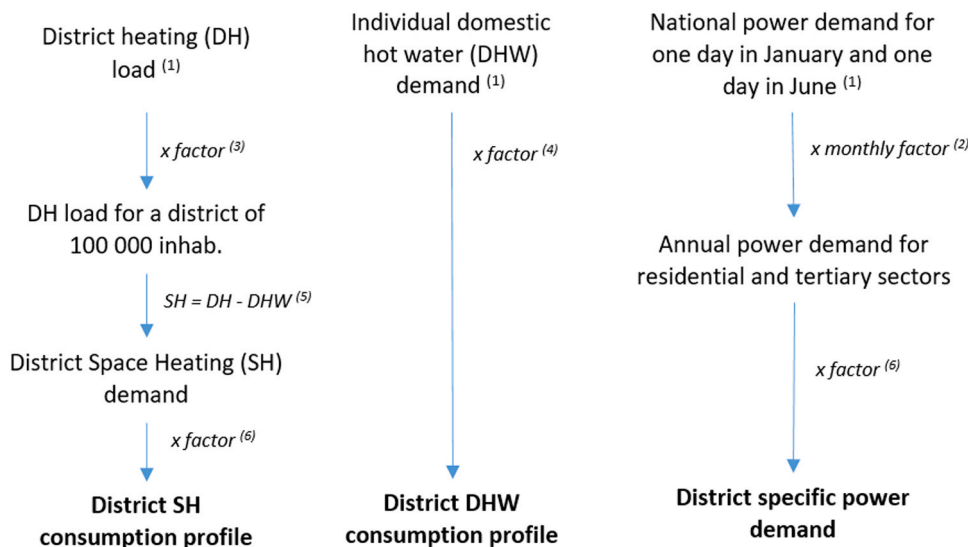


Figure 7. – Schéma de construction des séries temporelles de demande thermique du quartier

(1) District heating load profile is taken from a real district heating network. Domestic hot water load profile comes from measurements of a dwelling. Power demand profiles are based on the figure 2.4 in the 2019 RTE report (RTE, 2019b).

(2) The 2019 RTE report (RTE, 2019b) gives national power consumption by use, for one day in January and one day in June. For both daily profiles, we keep uses of residential and tertiary sectors. Then, we apply a multiplication factor to build profiles of the other months. Corresponding factors are given in Table 5 with the profile they referred to. Example: the consumption of a day of February is equal to this one of January multiplied by 0.97.

Table 5 Multiplication factors used by month to build power consumption profiles for all the year

	Factor	Référence profile
January	1	January
Fébruary	0,97	January
March	0,95	January
April	0,9	January
May	1,05	June
June	1	June
July	0,95	June
August	0,95	June
September	1,05	June
October	0,96	January
November	0,97	January
Décember	1	January

- (3) For a district of 100,000 inhabitants, we apply a multiplying factor to the district heating load such that the annual consumption is closed to 1 TWh according to national statistics (Ministère de la transition écologique et de la cohésion des territoires n.d.). In 2019 in France, residential park of 29,363 thousand houses has an annual heat consumption of 338.414 TWh.
- (4) Another multiplying factor is applied to individual DHW time serie such that the average DHW consumption and the average heat consumption on the DH network are closed in June. We supposed that this district heating has no industrial needs so that summer heat consumption is only domestic hot water demand.
- (5) The difference between DH load and DHW demand gives the space heating (SH) load profile. For days where DHW consumption is higher than DH load and the months of June, July and August, space heating load is set to 0.
- (6) At last, space heating and power load profiles are multiplied by a factor such that the annual ratio between all consumptions corresponds to this one given by national statistics (Ministère de la transition écologique et de la cohésion des territoires n.d.).

Appendice B. Impact of local heating electrification on power mix and national gas consumption

The following bar charts show the installed capacity of gas-fired plants and CHP in economic (Figure 8) and environmental (Figure 9) optimizations, for the five case studies of Table 4. The lines indicate the corresponding global gas consumption of each gas-fired plants, namely combine cycle gas turbines, combined heat and power plants (CHP), individual and large-scale gas boilers.

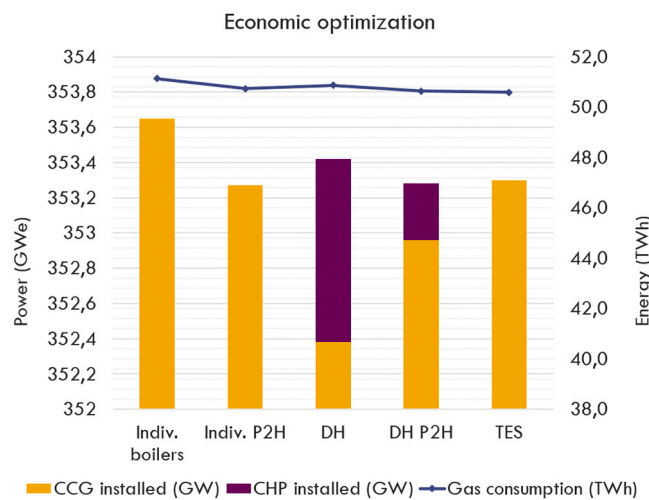


Figure 8. – Installed capacity of gas-fired plant (left axis) and gas consumption (right axis) for the five scenarios under economic optimization

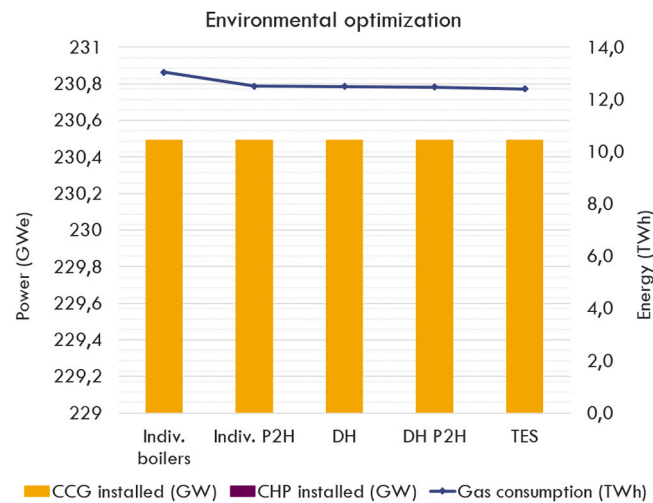


Figure 9. – Installed capacity of gas-fired plant (left axis) and gas consumption (right axis) for the five scenarios under environmental optimization

Figure 8 and Figure 9 show that no matter the optimization criteria, P2H introduction in the heating mix does not require supplementary gas-fired plant installed. Furthermore, the global gas consumption decreases.

Data Availability

I have specified in the article data sources.

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