

SUPPLEMENTARY MATERIAL

Table S.1 presents the input data for the energy model. The study was done for a full year of operation at an hourly time step. Parameters having more than one possible value are optimization parameters.

Table S.1. Input data for the energy model.

Magnitude	Value(s) or limit(s)	Units	Reference
Initial time of simulation (t_{ini})	0	h	[22]
Final time of simulation (t_f)	8760	h	[22]
Time step (Δt)	1	h	[22]
Electricity-to-heat conversion ratio with waste heat, ξ	0.85	kW _{th} / kW _{el}	[22]
Heat pump's performance ($COP_{HP}(T_{HP}^{in} = 35\text{ }^\circ\text{C})$)	3	kW _{th} / kW _{el}	[22]
Heat pump's performance ($COP_{HP}(T_{HP}^{in} = 50\text{ }^\circ\text{C})$)	4.29	kW _{th} / kW _{el}	[22]
Heat pump's maximum inlet power ($\dot{W}_{HP}^{el,max}(T_{HP}^{in} = 35\text{ }^\circ\text{C})$)	1260	kW _{el}	[22]
Heat pump's maximum inlet power ($\dot{W}_{HP}^{el,max}(T_{HP}^{in} = 50\text{ }^\circ\text{C})$)	881	kW _{el}	[22]
Thermal storage's maximum capacity (U_{TES}^{max})	[0, 10, 20, 30, 40]	MWh	[22]
Thermal storage's minimal time lapse for charge ($\Delta t_{TES}^{min,chg}$)	3	h	[6,34]
Thermal storage's minimal time lapse for discharge ($\Delta t_{TES}^{min,dchg}$)	3	h	[6,34]

Table S.2 presents the energy balance in its concretized formulation for each unit of the case study. Each balance is accompanied by its auxiliary equations. Maximal charge/discharge powers of the storage units were estimated through typical charge/discharge times published in the literature for thermocline storage units [34,35]. The COP value of 3 for the heat pump corresponds to a commercial unit that was identified at an early stage of the project. From there, it was assumed that the heat pump's second law efficiency remains the same independently of the inlet temperature. That assumption allowed to recalculate the COP and the maximal electric inlet power at the inlet temperature of 50 °C. The inlet energy of the HS (chemical exergy) was estimated by assuming an exergy efficiency for combustion processes [36,37].

Table S.2. Formulation of the energy balance for every unit in the study case.

Unit	Energy balance	Auxiliary equations
LNCMI	$\dot{W}_{LNCMI}^{in} \cdot \xi = \dot{Q}_{LNCMI}^{out}$	-
DISS	$\dot{Q}_{LNCMI}^{out} = \dot{Q}_{DISS}^{in} + \dot{Q}_{TES}^{in}$	$\dot{Q}_{TES}^{in,max} \leq U_{TES}^{max} / \Delta t_{TES}^{min,chg}$
TES	$\Delta U_{TES} = \dot{Q}_{TES}^{in} - \dot{Q}_{TES}^{out} - \dot{Q}_{TES}^L$	$\dot{Q}_{TES}^{out,max} \leq U_{TES}^{max} / \Delta t_{TES}^{min,dchg}$
HP	$\dot{Q}_{HP}^{in} + \dot{W}_{HP}^{in} = \dot{Q}_{HP}^{out}$ $\dot{Q}_{HP}^{in} = \dot{Q}_{TES}^{out}$ $COP_{HP} = \dot{Q}_{HP}^{out} / \dot{W}_{HP}^{in,elec}$	$COP_{HP}(T_{HP}^{in} = 35\text{ }^\circ\text{C}) = 3$ $\frac{COP_{HP}(T_{HP}^{in} = 50\text{ }^\circ\text{C})}{COP_c(T_{HP}^{in} = 50\text{ }^\circ\text{C})} = \frac{COP_{HP}(T_{HP}^{in} = 35\text{ }^\circ\text{C})}{COP_c(T_{HP}^{in} = 35\text{ }^\circ\text{C})}$ $COP_c = T_{HP}^{out} / (T_{HP}^{out} - T_{HP}^{in})$ $\dot{Q}_{HP}^{out,max}(T_{HP}^{in} = 50\text{ }^\circ\text{C}) = \dot{Q}_{HP}^{out,max}(T_{HP}^{in} = 35\text{ }^\circ\text{C})$
HS	$\dot{E}n_{HS}^{in} \cdot \eta_{HS} = \dot{Q}_{HS}^{out}$	$\eta_{HS} = \frac{\dot{Q}_{HS}^{out} / \theta_q(T = T_{HS}^{q,out})}{\dot{E}n_{HS}^{in} / \theta_{ch}}$ $\theta_q(T = T_{HS}^{q,out}) = 1 - \frac{T_0}{T_{HS}^{q,out}}$ $(\theta_{ch} \approx 1, T_0 = 8\text{ }^\circ\text{C})$
DHN	$\dot{Q}_{DHN}^{in} = \dot{Q}_{DHN}^{out}$	$\dot{Q}_{HP}^{out} + \dot{Q}_{HS}^{out} = \dot{Q}_{DHN}^{in}$
SST	$\dot{Q}_{SST}^{in} = \dot{Q}_{SST}^{out}$	$\dot{Q}_{DHN}^{out} = \dot{Q}_{SST}^{in}$

Table S.3 presents the input parameters for the exergy model. New information with respect to the energy model includes temperature levels and some exergy efficiencies. The dead state temperature of 8 °C corresponds to the Isère river's minimal temperature throughout the year.

Table S.3. Input data for the exergy model (to be aggregated to that in the energy model).

Model	Magnitude	Value(s) or limit(s)	Units	Reference
Exergy	Dead state temperature (T_0)	8	°C	[22]
	Heat supply unit's exergy efficiency (ϵ_{HS})	0.2	kW _{ex} / kW _{ex}	[22]
	Temperature difference for magnets' cooling ($\Delta T_{cooling}$)	60	°C	[26]
	Waste heat temperature (T_{wh})	[35, 50, 85]	°C	[22]
	Heat pump's inlet temperature (T_{HP}^{in})	[35, 50]	°C	[22]
	Heat pump's outlet temperature (T_{HP}^{out})	85	°C	[22]
	Heat supply unit's service temperature ($T_{HS}^{q,out}$)	120	°C	[22]
	End-users heat temperature	60	°C	[22]

Table S.4 summarizes all exergy balances in this study. The balance on the LNCMI's experiments dissociates exergy destruction into two terms. The first one was called 'useful' exergy destruction ($\dot{E}_{LNCMI}^{D,use}$). It was understood as the difference between input electricity to the magnets, and heat dissipated at the magnet's temperature. This exergy destruction allows the magnetic fields that yield results for the researchers. Thus, this exergy destruction was not accounted for in the LNCMI's exergy indicators. The second term of exergy destruction englobes the rest of inefficiencies, due to friction losses, heat exchanges... Those were indeed accounted for in the indicators.

Table S.4. Formulation of the exergy balance for every unit in the study case.

Unit	Exergy balance	Auxiliary equations
LNCMI	$\dot{E}_{LNCMI}^{in} = \dot{E}_{LNCMI}^{D,use} + \dot{E}_{LNCMI}^{out,q} + \dot{E}_{LNCMI}^D$	$\dot{E}_{LNCMI}^{in} = \dot{W}_{LNCMI}^{in}$
		$\dot{E}_{LNCMI}^{out,q} = \dot{W}_{LNCMI}^{in} \cdot \xi \cdot \theta_q(T = T_{LNCMI}^{out,q})$
		$\dot{E}_{LNCMI}^{D,use} = \dot{W}_{LNCMI}^{in} \cdot \xi \cdot (\theta_{elec} - \theta_q(T = T_{LNCMI}^{magnets}))$
		$T_{LNCMI}^{magnets} = T_{LNCMI}^{out,q} + \Delta T_{cooling}$
DISS	$\dot{E}_{DISS}^D = \dot{E}_{DISS}^{in,q}$	$\dot{E}_{LNCMI}^{out,q} = \dot{E}_{DISS}^{in,q} + \dot{E}_{TES}^{in,q}$
TES	$\dot{E}_{TES}^{in,q} = \dot{E}_{TES}^{out,q} + \Delta E_{TES}^u + \dot{E}_{TES}^L$	$\dot{E}_{TES}^L = \dot{Q}_{TES}^L \cdot \theta_q(T = T_{TES}^{in,q})$
HP	$\dot{E}_{HP}^{in,q} + \dot{W}_{HP}^{in} = \dot{E}_{HP}^{out,q} + \dot{E}_{HP}^D$	$\dot{E}_{HP}^{in,q} = \dot{Q}_{HP}^{in} \cdot \theta_q(T = T_{HP}^{in,q})$ $\dot{E}_{HP}^{out,q} = \dot{Q}_{HP}^{out} \cdot \theta_q(T = T_{HP}^{out,q})$
HS	$\dot{E}_{HS}^{in,ch} \cdot \epsilon_{HS} = \dot{E}_{HS}^{out,q}$	$\epsilon_{HS} = 0.4$ $\dot{E}_{HS}^D = \dot{Q}_{HS}^{out} \cdot \theta_q(T = T_{HS}^{q,out}) \cdot \left(\frac{1}{\epsilon_{HS}} - 1\right)$
DHN	$\dot{E}_{HS}^{out,q} + \dot{E}_{HP}^{out,q} = \dot{E}_{DHN}^{out,q} + \dot{E}_{DHN}^D$	-
SST	$\dot{E}_{SST}^{in,q} = \dot{E}_{SST}^{out,q} + \dot{E}_{SST}^D$	$\dot{E}_{DHN}^{out,q} = \dot{E}_{SST}^{in,q}$

Table S.5 introduces the input parameters for the economic and exergoeconomic models. Since this project is at a rather advanced stage, most of the investment costs and energy selling/buying costs are known from the real data. Fuel costs for the CCIAG's heat production plants are an educated guess, based on in-person and confidential communication with those stakeholders.

Table S.5. Input data for the economic and exergoeconomic models (to be aggregated to the energy and exergy models).

Magnitude	Value(s) or limit(s)	Units	Reference
Heat pump's purchase equipment cost ($PEC_{HP}(T_{HP}^{q,in} = 35 \text{ °C})$)	810	k€	[38]
Heat pump's purchase equipment cost ($PEC_{HP}(T_{HP}^{q,in} = 50 \text{ °C})$)	526	k€	[38]
Coefficient of thermal storage's purchase cost (c_{TES}^{PEC})	90	k€/MWh-capacity	[39]
Coefficient of piping costs (c_k^{pipe})	0.7	k€/(k€ of PEC)	[40]
Coefficient of operation and maintenance costs (c_k^{OM})	0.1	k€/(k€ of TCI)	[40]
Economic observation period (n)	20	years	[40]
Effective rate of return (i)	0.06	-	[40]
Specific buying price of the HS unit's fuel	40	€/MWh _{chem}	Confidential
Specific buying price of electricity from the grid (c^{elec})	120	€/MWh _{elec}	[23]
Specific selling price of heat for residential end-users ($c_{SST}^{q,out}$)	80	€/MWh _{heat}	[23]

Table S.6 presents the concretized model unit by unit. The main balances correspond rather to the economic model, and the auxiliary equations concern rather the exergoeconomic model. The LNCMI's waste heat price was estimated through their exergy balance, by neglecting the 'useful' exergy destruction as explained in the previous subsection. Thus, the working hypothesis is that revenues from selling waste heat should just compensate 'non-useful' exergy destructions of their experiments.

Table S.6. Formulation of the cost flow balance for every unit in the study case.

Unit	Cost flow balance	Auxiliary equations
LNCMI	$\dot{C}_{LNCMI}^D = \dot{C}_{LNCMI}^{q,out}$	$c_{LNCMI}^{W,in} = c^{elec}$
DISS	$\dot{C}_{DISS}^{q,in} = \dot{C}_{DISS}^D$	$c_{DISS}^{q,in} = c_{LNCMI}^{q,out}$
TES	$\dot{C}_{TES}^{q,in} + \dot{Z}_{TES} = \dot{C}_{TES}^{q,out}$	$c_{TES}^{q,in} = c_{LNCMI}^{q,out}$
HP	$\dot{C}_{HP}^{q,in} + \dot{C}_{HP}^{elec,in} + \dot{Z}_{HP} = \dot{C}_{HP}^{q,out}$	$c_{HP} = c_{TES}^{q,out}$
		$c_{HS}^F = c_{SST}^{out,REF} \cdot \dot{E}_{SST,REF}^{q,out} / \dot{E}_{HS,REF}^{F,in}$
HS	$\dot{C}_{HS}^F = \dot{C}_{HS}^{q,out}$	$c_{HS}^{q,out} = (c_{SST}^{q,in} \cdot \dot{E}_{SST,REF}^{in}) / \dot{E}_{HS,REF}^{q,out}$
		$c_{HS}^F = (c_{HS}^{q,out} \cdot \dot{E}_{HS,REF}^{q,out}) / \dot{E}_{HS,REF}^F$
		$\dot{Z}_{HS} = (\dot{C}_{SST,REF}^{q,out} - \dot{C}_{HS,REF}^{En,in}) / 3$
DHN	$\dot{C}_{HP}^{q,out} + \dot{C}_{HS}^{q,out} = \dot{C}_{DHN}^{q,out}$	$\dot{Z}_{DHN} = (\dot{C}_{SST,REF}^{q,out} - \dot{C}_{HS,REF}^{En,in}) / 3$
		$c_{SST}^{q,in} = c_{DHN}^{q,out}$
SST	$\dot{C}_{SST}^{q,in} = \dot{C}_{SST}^{P,BEP}$	$c_{SST}^{q,in} = \dot{C}_{SST,REF}^{q,out} / \dot{E}_{SST,REF}^{q,in}$
		$\dot{Z}_{SST} = (\dot{C}_{SST,REF}^{q,out} - \dot{C}_{HS,REF}^{En,in}) / 3$

For the CCIAG, amortization requirements on their existing units (HS, DHN and SST) were also taken into account. They were estimated through the difference between total heat revenues and total fuel costs, at the reference scenario. 'Reference scenario' means that all of the district's heat needs are covered by the CCIAG's production plants. Those amortization requirements were equally distributed between the three units. As it will be explained in the next subsection, it was assumed that the CCIAG may relax their conditions by partially disregarding those amortizations. This would allow them to buy the recovered heat at a higher price, facilitating the project's feasibility for all stakeholders.

Figures S.1 to S.4 display how the socio-energetic nodes are structured for this case study in each of the ownership scenarios under consideration. Performance indicators are defined in accordance to these socio-energetic nodes (refer to Table 2 of the main manuscript).

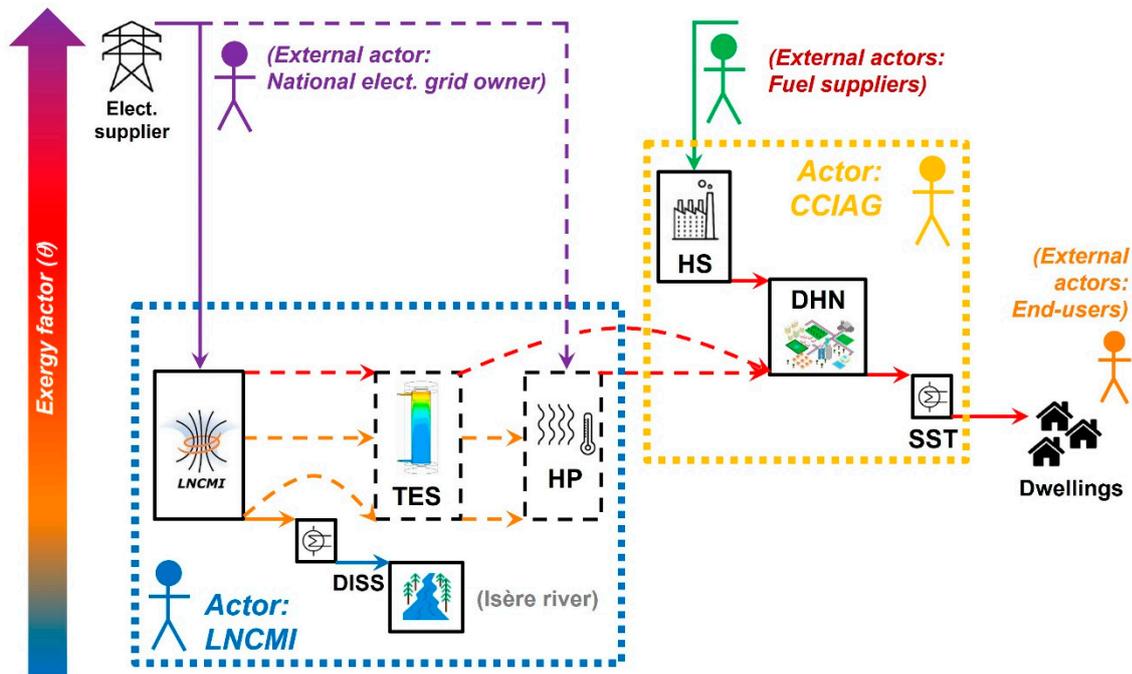


Figure S.1. Depiction of the socio-energetic nodes in Scenario 1, where LNCMI is the owner of the prospective energy system.

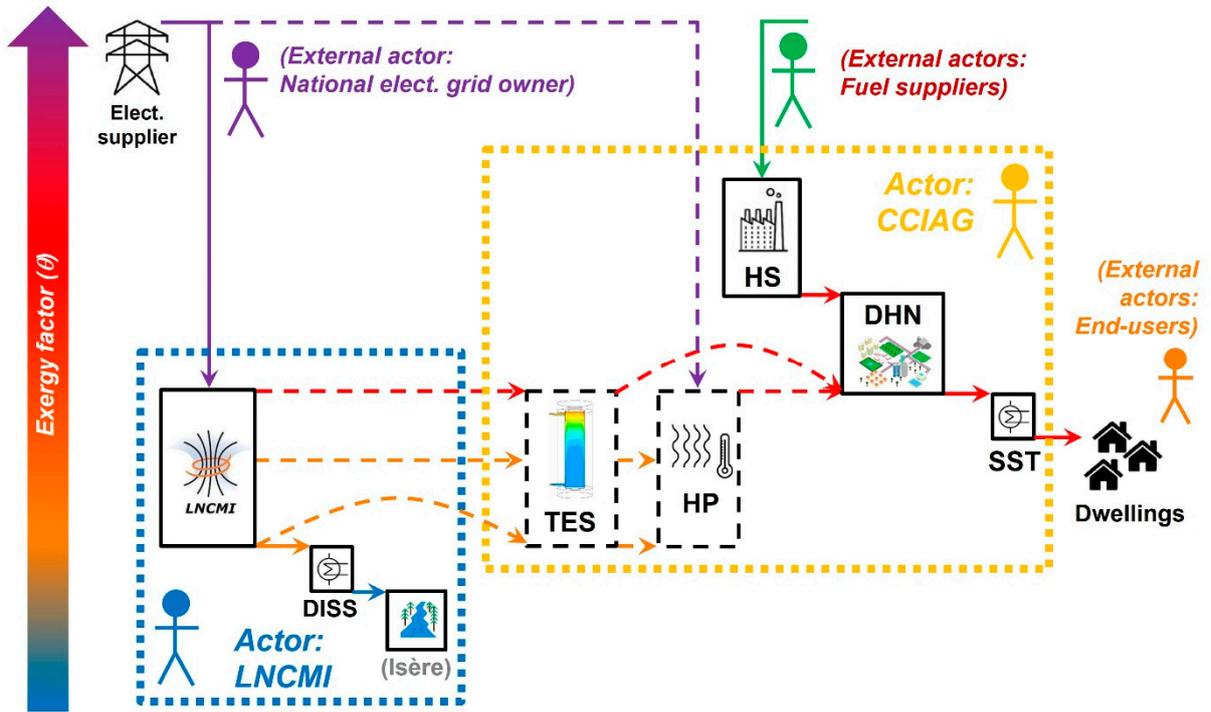


Figure 5.2. Depiction of the socio-energetic nodes in Scenario 2, where CCIAG is the owner of the prospective energy system.

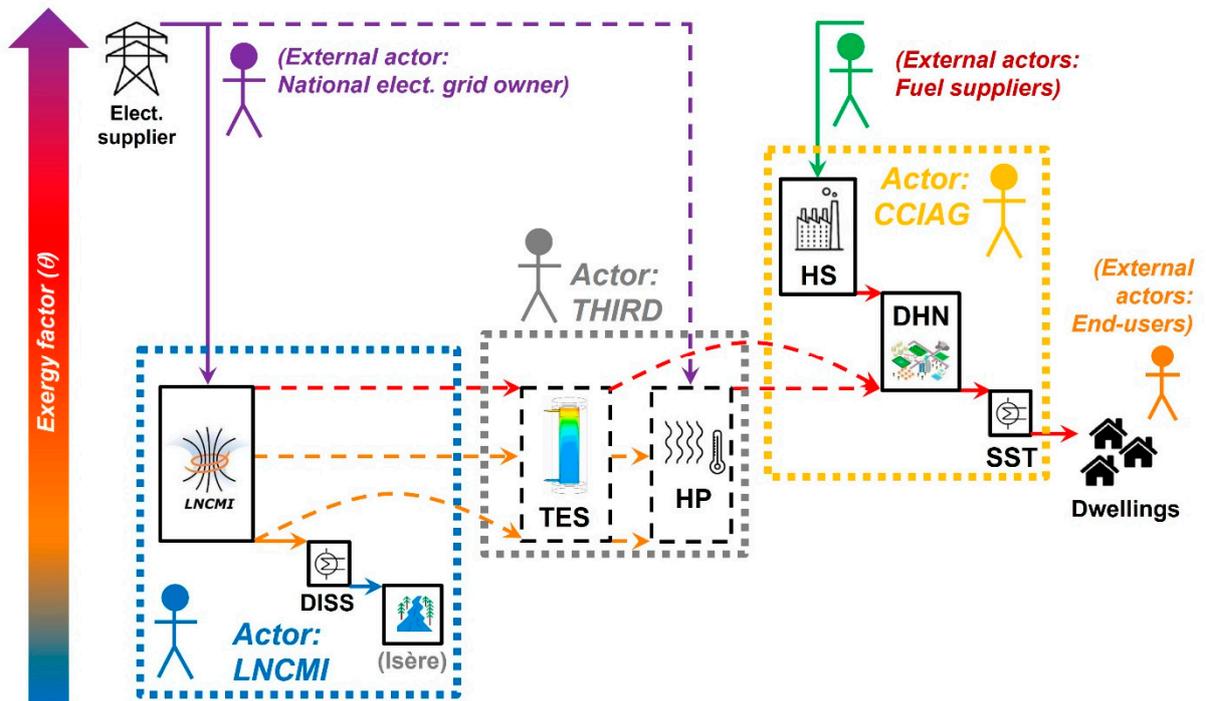


Figure 5.3. Depiction of the socio-energetic nodes in Scenario 3, where THIRD is the owner of the prospective energy system.

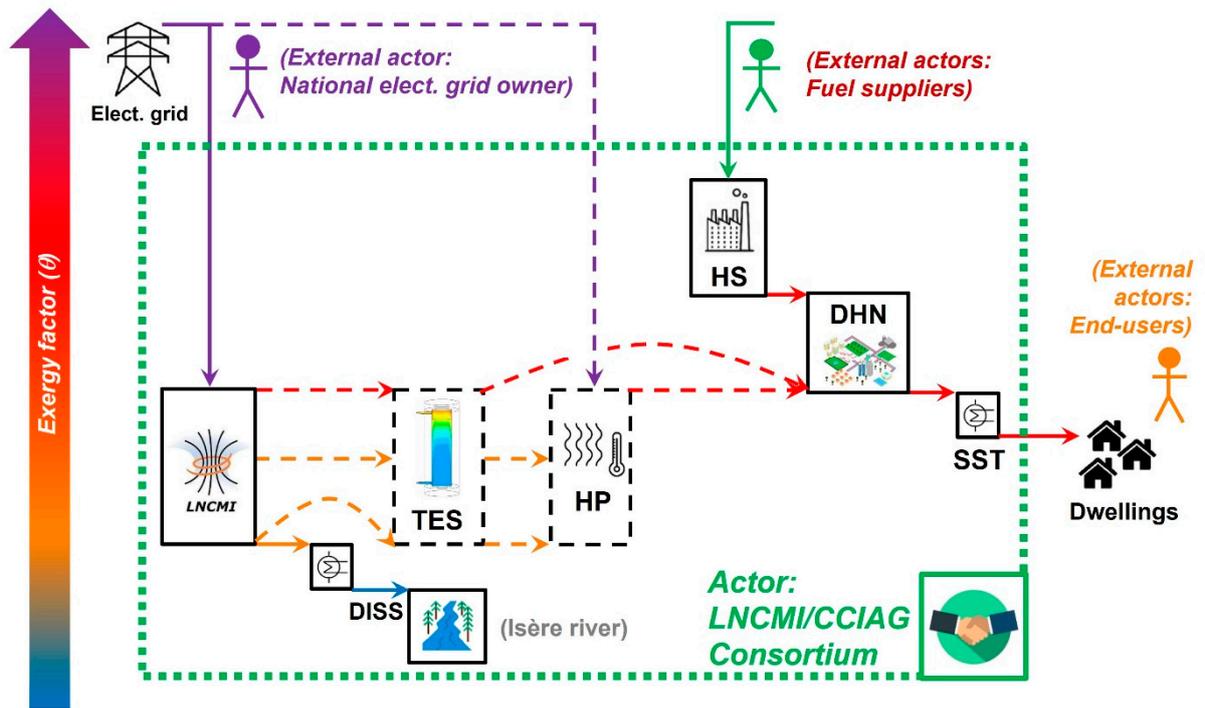


Figure S.4. Depiction of the socio-energetic nodes in Scenario 4, where a LNCMI/CCIAG consortium is the owner of the prospective energy system.