Signal-driven demand-side flexibility for the smart electrification of heating and cooling

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1 Context of the study

In 2019, IRENA released a report titled *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* [1]. It encompasses a series of innovations to create a systemic approach on the integration of variable renewable energy sources (VRE) into the gird. The analysis also demonstrates that innovations are emerging across four key dimensions of the world's power systems, and that to create solutions to modern power systems it is necessary to cross-correlate and combine innovations in:

- Technology and infrastructure
- Business models
- Market design and regulation
- System operation and planning

In 2022, the Innovation Landscape Report 2 is going to be published by IRENA. This new document is intended as a repository of innovations for the smart electrification of end-use sectors in 3 different vectors: power-to-mobility, power-to-molecules, and power-to-heating-and-cooling. As in the previous iteration of the Innovation Landscape Report, it is intended to preserve the systemic approach across the 4 dimensions stated above.

The Innovation Landscape Report 2 motivated a side project to assess the impact of these innovations on the electricity grid and how smart electrification of end-use sectors can decarbonize the economy not only by getting rid of fossil-fueled obsolete technologies in mobility and heating sectors, but also by providing flexibility and ancillary services to power systems and incentivizing the deployment of VRE.

The innovations for the vector of heating and cooling are presented in the following figures:

*International Renewable Energy Agency (IRENA)

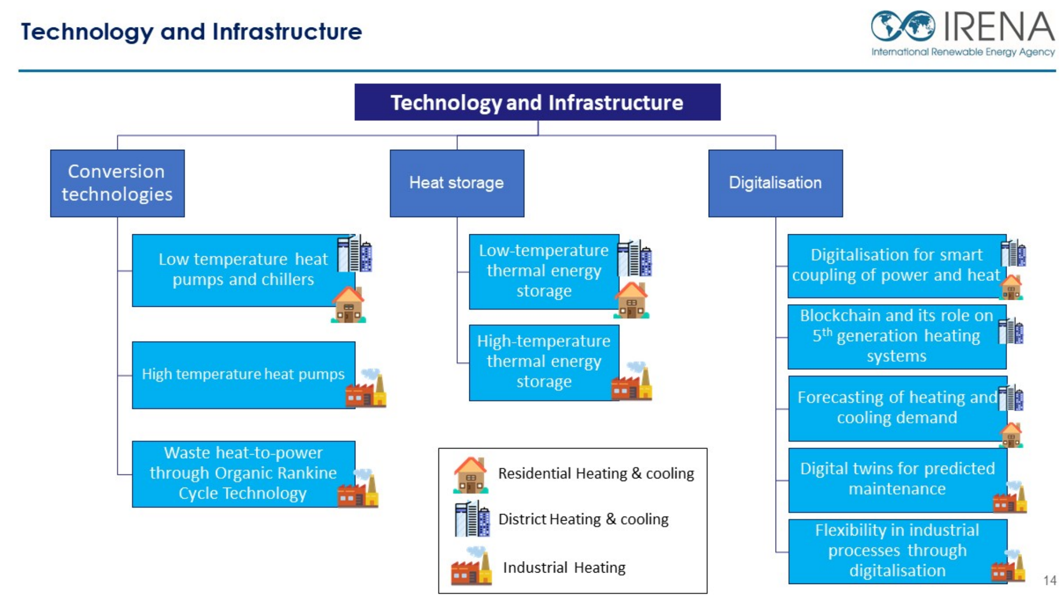

Figure 1: Technology and infrastructure innovations

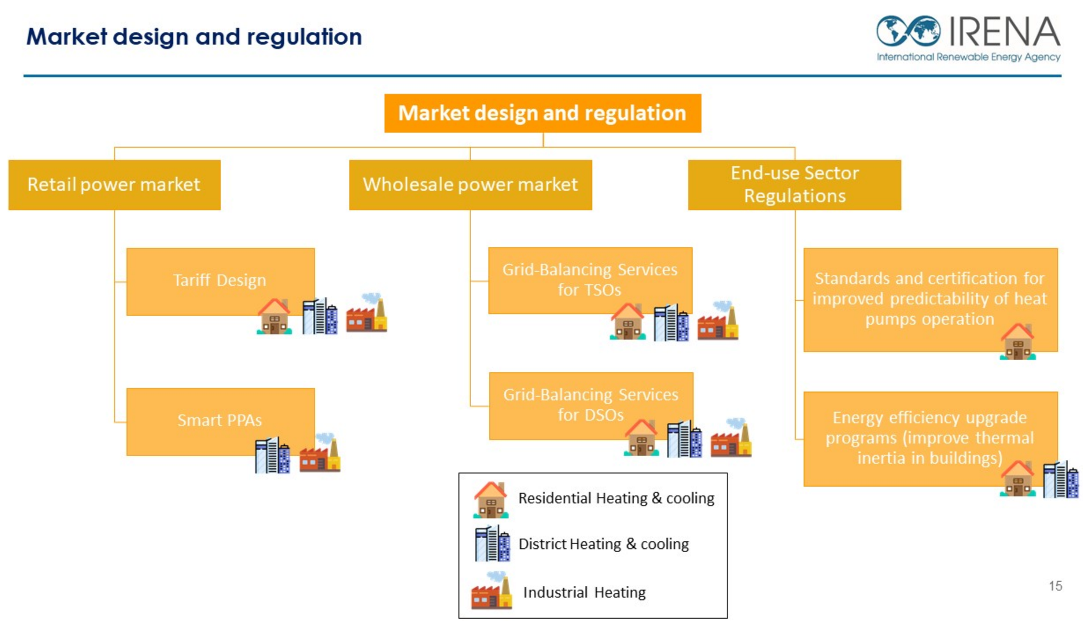

Figure 2: Market design and regulation innovations

To assess the impact of smart electrification on the demand-side flexibility of heating systems, we propose a signal-driven flexibility scheme, in which the user will react to a signal (or multiple signals) to change its behavior of power consumption for heating purposes, and reflect some of the aforementioned innovations

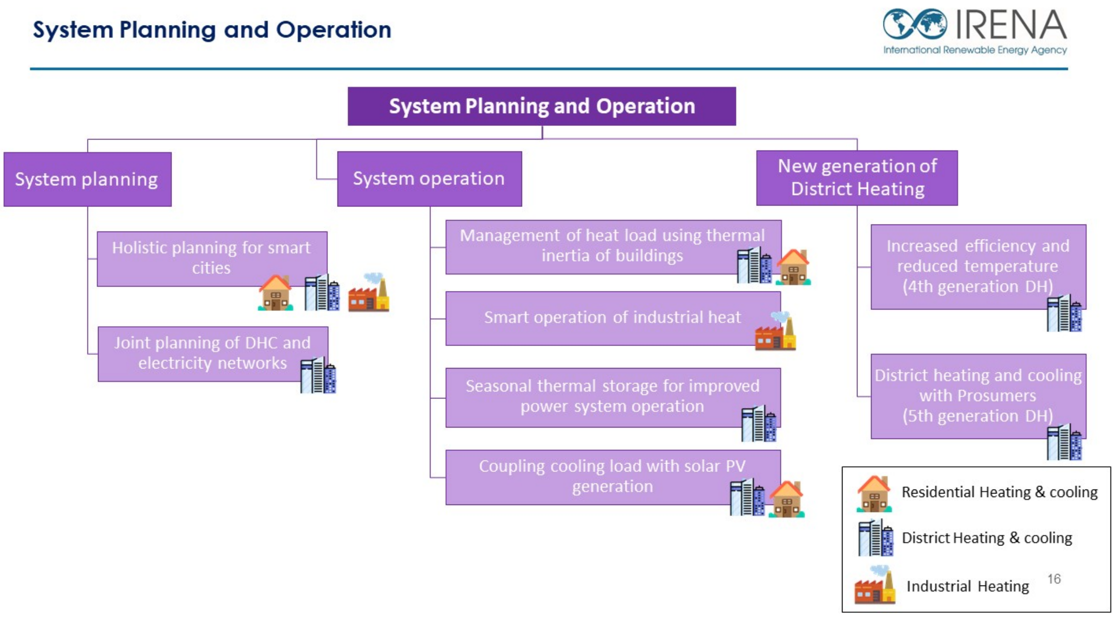

Figure 3: System operation innovations

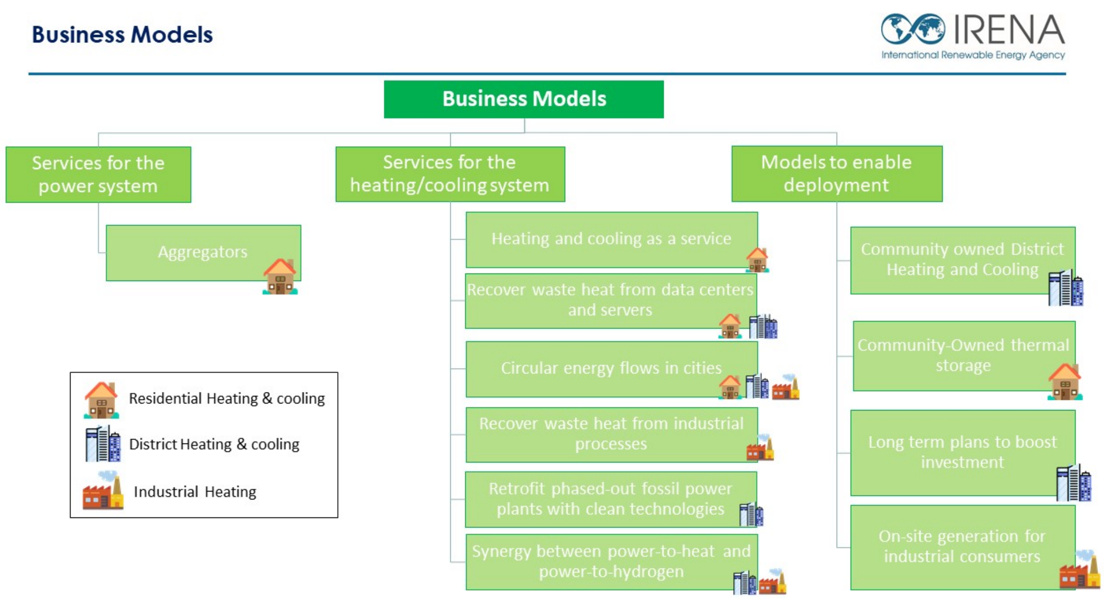

Figure 4: Business models innovations

in physical properties of buildings.

2 Non-flexible heating profiles

Non-flexible heating profiles are created with the Swiss CESAR model [2] for commercial and residential buildings. The archetypal heating profiles are in an hourly temporal resolution, and cover an entire year in Switzerland. Profiles for the following buildings are extracted from [3]:

- Single family households
- Multifamily households
- Hospitals
- Schools
- Offices
- Shops
- Restaurants

3 Signals

A signal can be any vector or profile that could trigger a change in behavior of the user. This vector can be a dynamic pricing of electricity, the day-ahead market, a bid from the TSO to buy ancillary services from aggregators at specific hours, etc. For this demonstration ENTSO-E's day ahead market for Switzerland is utilized.

4 Flexible heating demand

Given a signal $\boldsymbol{\xi} \in \mathrm{R}^{24}$ and an hourly non-flexible heating demand profile $\boldsymbol{q} \in \mathrm{R}^{24}$, we define the flexible heating demand as

$$\boldsymbol{x} = \text{flex}\left(\boldsymbol{\xi}, \boldsymbol{q}\right), \tag{1}$$

where flex $(\boldsymbol{\xi}, \boldsymbol{q})$ is an optimization program defined as:

$$
\begin{aligned}
\operatorname{flex}(\boldsymbol{\xi}, \boldsymbol{q}) = \underset{\boldsymbol{x},\, \boldsymbol{T}^x}{\text{minimize}} \quad & \boldsymbol{\xi}^\intercal \boldsymbol{x} \\
\text{subject to} \quad & \overline{q} = \begin{cases} k^q \left(T^q - \overline{T}^{out} \right) & \text{for} \quad q_i > 0 \\ 0 & \text{elsewhere} \end{cases}, \\
& \boldsymbol{x} = \begin{cases} k^x \left(\boldsymbol{T}^x - \boldsymbol{T}^{out} \right) & \text{for} \quad T_i^x \geq T_i^{out} \\ 0 & \text{elsewhere} \end{cases}, \\
& T^q - 3 \geq T_i^x \geq T^q + 3, \\
& x_i - q_i \geq -.4 \left\| \boldsymbol{q} \right\|_\infty, \\
& \mathbf{1}^\intercal \boldsymbol{x} = \mathbf{1}^\intercal \boldsymbol{q}, \\
& x_i \geq 0,
\end{aligned} \tag{2}
$$

Each set of constraints will be explained next, as there are two different types of connstraints: physical constraints, that are defined by the physics of heat conduction and convection of buildings, and artificial contraints, that reflect different system limitations that have been found experimentally and are reflected on the literature.

4.1 Building energetics

The first set of constraints correspond to physical constraints. The temperature of the non-flexible building is set to be a fixed value T_q (that could be 21 or 22 $^\circ C$), and we set another decision variable for the temperature inside the building with flexible demand $\boldsymbol{T_x}$ such that $\boldsymbol{T_x} \in [T_q - 3^\circ C, \quad T_q + 3^\circ C]$.

Of course, the inside temperature of buildings is strictly related to the energy flow of the building system:

$$
\boldsymbol{q} = A_{th} \left(k_{th}^q \left(T_q - \boldsymbol{T_{ext}} \right) - k_{sun}^q \dot{\boldsymbol{i}} \right) - \dot{\boldsymbol{Q}}_{\boldsymbol{people}} - \dot{\boldsymbol{Q}}_{\boldsymbol{el}}, \tag{3a}
$$

$$
\boldsymbol{x} = A_{th} \left(k_{th}^x \left(\boldsymbol{T_x} - \boldsymbol{T_{ext}} \right) - k_{sun}^x \dot{\boldsymbol{i}} \right) - \dot{\boldsymbol{Q}}_{\boldsymbol{people}} - \dot{\boldsymbol{Q}}_{\boldsymbol{el}}, \tag{3b}
$$

where

- $\dot{\boldsymbol{Q}}_{\boldsymbol{people}}$ $[kW]$ is the heat gain due to people
- $\dot{\boldsymbol{Q}}_{\boldsymbol{el}}$ $[kW]$ is the heat gain due to electric appliances inside the building
- $\boldsymbol{T_{ext}}$ $[^\circ C]$ is a vector of external temperatures throughout the day
- $\boldsymbol{i}$ $[kW/m^2]$ is the solar irradiance
- k_{th} $[kW/m^2 K]$ is a thermal coefficient for losses due to ventilation and building design
- k_{sun} [-] is the solar irradiance coefficient

- A_{th} $[m^2]$ is the building heated surface

But as it can be seen, this problem is non-linear, and the number of variables is now greater than the number of equations. We are expecting to find a set of equations that could satisfy linear constraints with proper assumptions.

Neglecting the heat gained by people, electronic appliances and sun irradiation (a long stretch) we were able to simulate the heat conduction losses by defining a mean k_{th} from the values in which the demand of the building is non-zero:

$$\overline{q} = \begin{cases} k^q \left(T^q - \overline{T}^{out}\right) & \text{for} \quad q_i > 0 \\ 0 & \text{elsewhere,} \end{cases} \tag{4}$$

Like-wise, the temperature and the heating demand of the flexible building can be linked in a similar manner, by respecting the constraint of the ± 3 degrees:

$$\boldsymbol{x} = \begin{cases} k^x \left(\boldsymbol{T}^x - \boldsymbol{T}^{out}\right) & \text{for} \quad T_i^x \geq T_i^{out} \\ 0 & \text{elsewhere} \end{cases}, \tag{5a}$$

$$T^q - 3 \geq T_i^x \geq T^q + 3, \tag{5b}$$

4.2 Energy balance, efficiency, and peak demand

This set of constraints are called artificial constraints, since they are not linked to any heat transfer property.

This program accounts for energy conservation (the total energy demanded of the non-flexible profile is the same as in the flexible demand):

$$\mathbf{1}^\intercal \boldsymbol{x} = \mathbf{1}^\intercal \boldsymbol{q}, \tag{6}$$

This constraint however, can be modified to reflect energy efficiency in heat pumps. If a global efficiency coefficient ϵ is defined, then the constraint can be rewritten as:

$$\mathbf{1}^\intercal \boldsymbol{x} \geq (1 - \epsilon)\, \mathbf{1}^\intercal \boldsymbol{q}, \tag{7}$$

The program also assumes energy flows from the electricity grid to the heat pumps, meaning that heating demand can only be positive. This can be reflected in the following equation:

$$x_i \geq 0, \tag{8}$$

Finally, we set a constraint on the shape of the profile itself. Only 40% of the total peak demand can be shoved elsewhere, meaning that the program cannot artificially set another peak demand where the electricity is cheaper. This is reflected in the following equation:

$$x_i - q_i \geq -.4 \, \|\boldsymbol{q}\|_\infty \tag{9}$$

5 Results

In figure 5 the results for a winter day in an office building are displayed. As it can be seen, the peak was shoved to accommodate for more affordable pricing of electricity, respecting the constraints, thus creating a flexible profile.

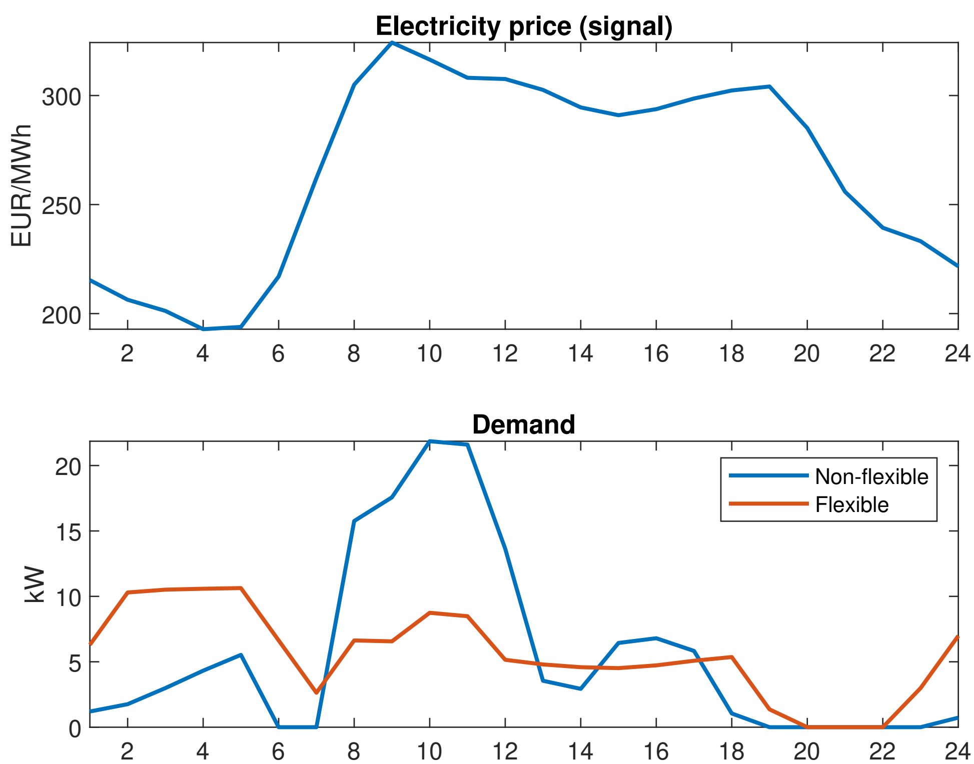

Figure 5: Results for an office building in a winter day

References

[1] IRENA. Innovation landscape for a renewable-powered future, 2019. 1

[2] Danhong Wang, Jonas Landolt, Georgios Mavromatidis, Kristina Orehounig, and Jan Carmeliet. Cesar: A bottom-up building stock modelling tool for switzerland to address sustainable energy transformation strategies. Energy and Buildings, 169:9–26, 2018. 2

[3] Selin Yilmaz, Portia Murray, Andrew Bollinger, and Gianfranco Guidati. HOURLY DEMAND PROFILES FOR SPACE HEATING AND ELECTRICITY. page 17. 2