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Article

Impact of Heat Pumps Flexibility in a French Residential Eco-District

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Abstract: This paper investigates how blocks of buildings could fit into load shedding strategies. It focuses in particular on what could be the effects on peak shaving, occupants' thermal comfort or CO_2 emissions reduction and how to quickly quantify them. To achieve this goal, we focused on a new residential district, thermally fed by heat pumps. Four modeling approaches were confronted in order to estimate buildings' responses to load shedding orders. On the one hand, a quick estimation of the peak shaving impact can rely on experimental results if the buildings' envelope and uses of the experimentation match those of the study case. On the other hand, thermal simulation models allow us to assess thermal comfort, while considering the building physical response. Finally, a hybrid modeling approach can provide a good compromise between modeling rapidity and accuracy of the impacts estimation. At district scale, it may be necessary to mix modeling approaches, from experimental results to detailed thermal models. Accuracy is not guaranteed for all approaches so that the choice should be made carefully in regards to study needs. However, results are sufficient to compare the effects of load shedding strategies on peak shaving, thermal comfort, and CO_2 emissions reductions.

Keywords: Peak Shaving; Demand Response; Block of Buildings; Thermal Model; TEASER

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1. Introduction

1.1. Background

Nearly 3 years after the 21th Conference of the Parties of the UNFCCC (COP21), lots of energy transition policies have been carried out in order to respect Paris Agreement by keeping the global average temperature below 2°C above pre-industrial levels.[1] The massive integration of renewable energy sources, together with the electrical peak consumptions augmentation put load flexibility in a central position into energy transition strategies, as it could help to guarantee grid stability.

Lots of new stakeholders, as well as new markets appear in order to modulate electrical consumption. However, aggregators mostly apply these demand response strategies on electricity intensive industries, excluding lower power level sites such as buildings. Nevertheless, the latter represent a large share of energy consumption, so that they can represent a significant amount of power if gathered. Thanks to their thermal inertia, they also appear as great candidate for short punctual or repeated heat load shedding orders, but this flexibility remains hard to quickly evaluate.

Therefore it became one of the key points studied into the European project City-zen.[2] Our work together with the local DSO (Distribution System Operator) GEG (Grenoble Electricity and Gas) takes place in this context and focus on a new residential eco-district. This district (23 buildings for 264 flats) is thermally fed by heat pumps, placing the heating as an electrical issue.

1.2. Context and aims of the study

Into the local context of Grenoble, an electrical morning consumption peak appears between 5am and 10am, so that GEG is interested in peak shaving by giving efficient load shedding orders. However, it could be hard to quickly quantify the impact of load shedding strategies on peak shaving, but also to avoid any occupants' thermal discomfort as well as any carbon footprint increase.

Indeed, the problem can be complex to model. On the one hand, in order to maintain the occupants thermal comfort, some load shedding can be realized after an over-heating so that the building could store heat before stopping the heating systems. On the other hand, as it induces an over-consumption, this over-heating should be performed before the peak period (in our case between 5am and 10am), when the purpose is to reduce the consumption peak. In order to study a strategy of district peak reduction by stopping the heating supply building by building, we will compare two load shedding strategies (with or without over-heating).

This paper aims to quickly quantify the influence of this district heat load shedding strategy on the heat load curve, the thermal comfort and greenhouse gases emissions reduction. Moreover, we will try to quantify the impact of the heat load profiles modeling on the results.

1.3. Literature review

The idea of using buildings' thermal inertia in order to modulate heating load becomes more and more studied into the literature [3–7]. Several methodologies have been developed in order to quantify this flexibility but only three are commonly applied using building structural mass only [8]. Moreover, only few of these papers evaluate impact on thermal comfort as they mostly consider it as a constraint [9]. In our case, we will consider the possibility to be out of the comfort zones, usually defined by set-point temperature ranges [6,10], while estimated this impact by standing on comfort ranges defined in [11].

Most of the time, estimating the building temperature is possible as the building thermal flexibility quantification is based on thermal models [6,12–14]. Even the district scale becomes more and more widespread into the energetic dynamic simulation softwares, as DIMOSIM (DIstrict MOdeller and SIMulator) developed by the CSTB [15], CEA (City Energy Analyst) from the Zurich ETH [16] or TEASER (Tool for Energy Analysis and Simulation for Efficient Retrofit) from RWTH [17]. However, it was shown that this scale change could be dangerous by being relevant for annual heating needs, but not anymore when focusing on power analysis [18]. For this reason, we decided to base our study on models with different levels of details.

2. Methods

2.1. Load shedding impact quantification

2.1.1. Peak shaving

In order to quantify at best the amount of load reduction into a district, we first have to define the indicators we will focus on. Many studies show some rebound effects after a load shedding, related to the restart of the consumption. In order to quantify the impacts of load shedding strategies for peak shaving purposes, we will rely on one indicator, based on this used by the French TSO RTE:

The load transfer rate (LT_{rate}), that we define here dynamically (the reported energy will be considered for each time slot during a day):

$$LT_{rate}[h;h+1] = \frac{E_{tr}[h;h+1]}{E_c} \tag{1}$$

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Defined as such, the load transfer rate can be used to study dynamically the load variations and gives information on the efficiency of the load shedding strategy to reduce a long peak period (more than one hour).

2.1.2. Thermal comfort

It is important to keep in mind that stopping the heat supply can impact the thermal comfort, so that we have to estimate this aspect too. To do so, we will focus on the operative temperature (T_{op}), defined as follows:

$$T_{op} = \frac{T_{walls} + T_{air}}{2} \quad (2)$$

This operative temperature will allows us to estimate the comfort level, according to levels defined in [11]:

- Comfortable: A range of +/- 1°C about the temperature set-point (T_{set})
- Slightly uncomfortable: A range of +/- 1°C and +/- 2°C about T_{set}
- Uncomfortable: A difference of more than 2°C with T_{set}

2.1.3. CO_2 emissions reduction

Finally, we will study the impact of the different load shedding methods on CO_2 emissions. To do so, we will rely on the actual CO_2 emissions from the French power generation during January 2016 [19]. This will allow us to estimate the gross CO_2 emissions variation when the load shedding strategies will be applied, while taking into account hourly and daily variation.

We will also introduce the energy savings rate (ES_{rate}), defined 23 hours after the load shedding (the reported energy will be considered as the sum of the transfered energy for all time slots until 23 hours after the load shedding):

$$ES_{rate} = \frac{E_c - E_a - E_{tr}}{E_c} \quad (3)$$

The energy saving rate is commonly used to quantify energy sobriety in the long-run by showing the amount of non-reported energy 23 hours after. Thank to this indicator, it is thus possible to look at both the impact of the load shedding strategy on CO_2 emissions reduction and the linked with energy savings.

Table 1. Nomenclature indicators

Term	Signification
E_a	Anticipated energy consumption
E_c	Cut-off energy consumption
E_{tr}	Transfered energy consumption
ES_{rate}	Energy savings rate
LT_{rate}	Load transfer rate
T_{air}	Ambient temperature
T_{set}	Set-point temperature
T_{op}	Operative temperature
T_{walls}	Walls temperature

2.2. Heat load profiles models

According to the indicators previously defined, we need to assess at least the heat load variation between no-load shedding orders and the applied load shedding strategy in order to quantify the impact on peak shaving and CO_2 emissions.

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2.2.1. Experimental load transfer profile

A first estimation can rely on experimental results from similar buildings and load shedding strategies. The main advantage is to assess very quickly to peak shaving indicator. To do so, we will define a standard load transfer rate profile, based on experimental results from the French GreenLys project [20] and from a study led by the French TSO RTE.

As the experimental building stock contains two new eco-districts [20], we consider that the resulting standard profile can be used for our new residential district. The experimental results show a energy saving rate around 90% and the transfered energy rate profiles are plotted figures 1(**a**) and 1(**b**).

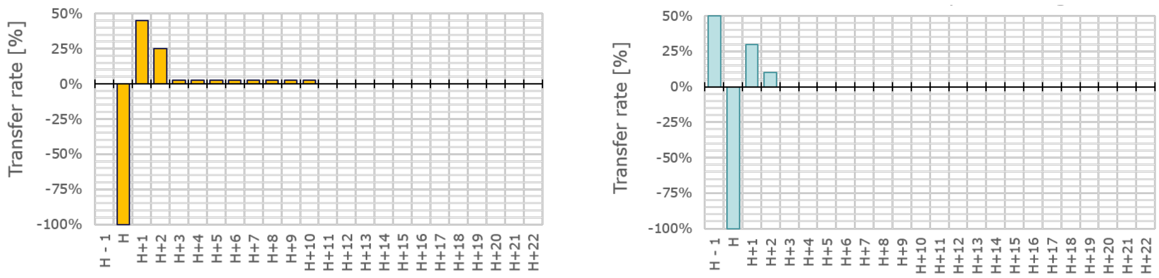

Figure 1. (**a**) One-hour residential heat load shedding without pre-heating (**b**) One-hour residential heat load shedding after one-hour pre-heating

2.2.2. Thermal models

However, in order to quantity impact on thermal comfort, it is also necessary to estimate T_{op} (cf. equation 2). For this reason, we used a thermal model with identified constants, in order to simulate the building dynamic after the load shedding. The first thermal model chosen (see figure 2) is generated by TEASER [21] and was studied with two precision levels. The second one is the fully detailed thermal model used for the mandatory study.

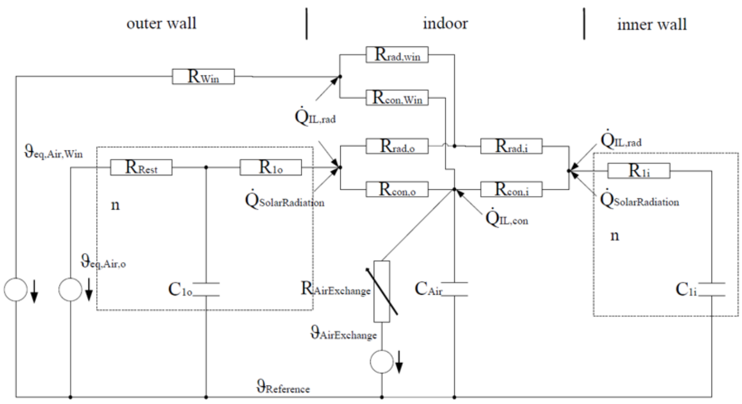

Figure 2. Scheme of the RC equivalent model generated by TEASER

In order to manage both the building thermal and the electrical grids models, while being an open-source tool, TEASER was chosen for thermal models creation. It allowed us to automatically generate RC thermal models in the Modelica language for the AixLib [22] and the Annex60 [23] libraries. The thermal model can be created thanks to building envelope information (wall areas, orientations, thickness, materials, ...). However, as it can be very difficult at district scale to access to the specific data about each building envelope, this can be realized with at least 5 inputs data : year of construction, net leased area, type of use, number of floors and height of floors [21], making the tool very useful to save time. If only theses data are given, the tool will enrich the dataset thanks to

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statistical data, whose use in a French context will be analyzed in this study case. We will use both the model generated with the 5 minimal parameters (further referred to the reduced model) and the model enriched with the building envelope data used for the regulatory Building Energy Simulation (BES) (further referred to the reduced enriched model).

In a French context, since each building construction requires an energetic study based on a fully detailed thermal model, we can also re-use existing thermal models from this mandatory study. In this study, we will re-use a Comfie & Pléiades fully detailed model, that will be called "complex model" afterwards.

For all heat load profiles from simulation models, we will consider as reference heat load profile, the result from a thermal dynamic simulation of a building in our district. We will simulate the building behavior in case of a temperature set-point of 20°C during the month of January, with a variable time step. All other data: weather, occupancy schedules, internal gains for lightning etc. have been set to the same values in order to get a better comparison between simulation results. However, the set-point temperatures for the Modelica models are ambient temperatures, while the Comfie + Pléiades control is on the operative temperature. Therefore, we could still expect small differences between the results.

2.3. Load shedding scenarios modeling

For these models, two scenarios will be studied :

- One-hour heat load shedding after one-hour over-heating
  In order to over-heat the building out of the peak period (5am to 10am), the load shedding order will be applied from 5am to 6am.
- Simple one-hour heat load shedding
  In this scenario, the load shedding order will be applied in the middle of the peak period, from 7am to 8am without any over-heating.

Each load shedding will be modeled as a very low set-point temperature (around 0°C) in order to cut the heat supply. The aim of these two scenarios is to represent the two load shedding types that could be made building by building into the district (see figure 3).

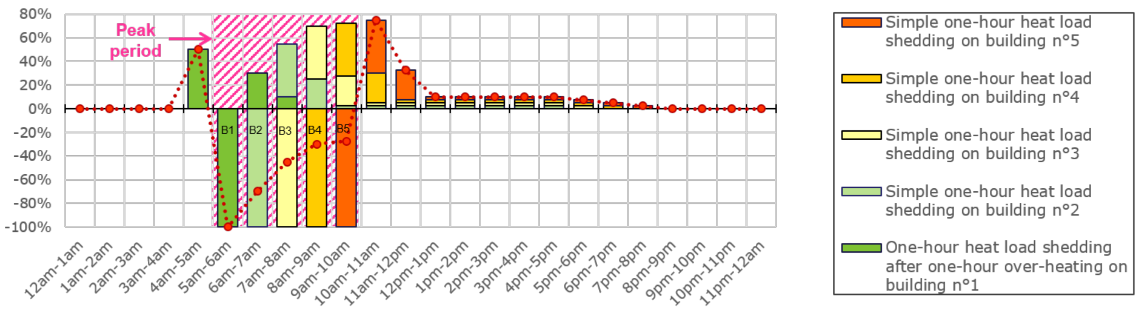

Figure 3. Daily transfer rates of the multiple one-hour heat load shedding from 5am to 10am

3. Results

Here, we will analyze the load shedding impacts in terms of peak shaving, thermal comfort et CO_2 emissions.

Results for peak shaving

As explained previously, the district load-shedding strategy consists in cutting heating load from each building at a time during one-hour. The first load shedding would integrate a one-hour over-heating the previous hour, while all the following orders will be simple one-hour heat load shedding. Two different building behaviors are thus expected for these two strategies. In order to reduce the mean power during the peak period, the load transfer rate would have to be the more diffuse as possible to shift most of the consumption out of the peak period. Thus, the lower load transfer rate, the more the load shedding would be considered as efficient for peak shaving.

3.0.1. Simple heat load shedding from 7am to 8am

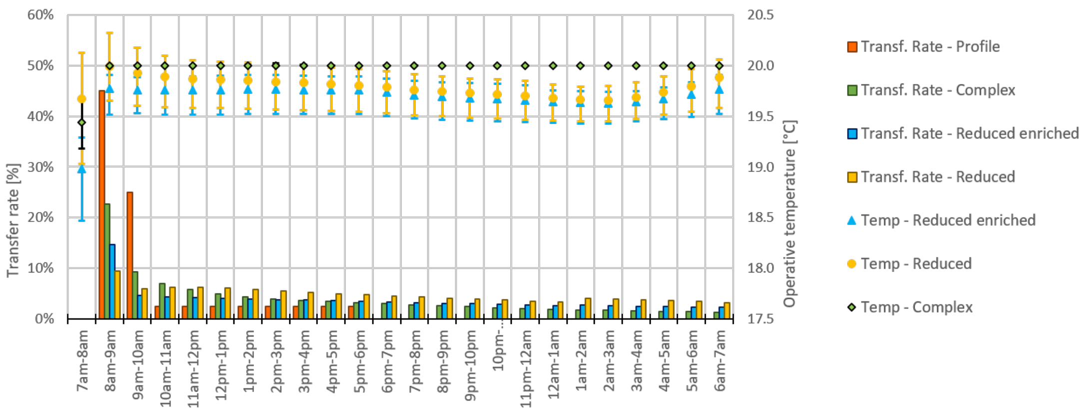

Figure 4. Simple one-hour heat load shedding

Two main building behavior can be observed :

- Most of the rebound effect appears within the two hours following the load shedding (experimental load transfer profile)
- The rebound effect is more diffuse with a load transfer during the entire day (load transfer profiles from thermal models)

Here, we can notice that all the simulation results from thermal models show a slower dynamic than the experimental load transfer profile. Although this last one was established from real measurement, it remains difficult to consider it as more reliable than simulated profiles, as several types of buildings are aggregated weather and occupancy data differ. Thus, we concluded that this load shedding strategy could be efficient in regard to a peak shaving objective.

3.0.2. Complex heat load shedding from 5am to 6am after an over-heating from 4am to 5am

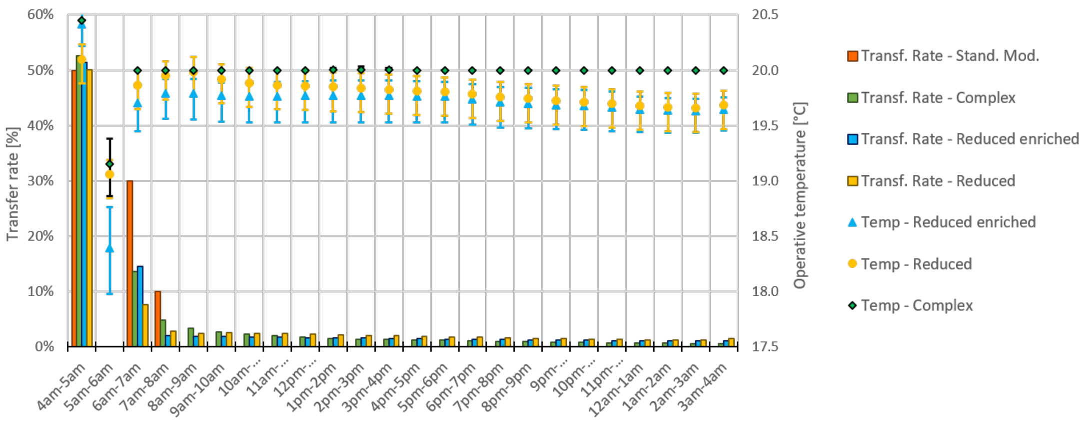

Figure 5. Complex one-hour heat load shedding after one-hour over-heating

As seen before, we have a big difference between experimental and simulated buildings behavior for simple heat load shedding strategy. This gap between models is confirmed for this complex

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strategy too, so that beginning with an over-heating still lead to diffuse load transfer report. We can conclude that the load shedding strategy designed for the entire district could be efficient in term of peak shaving, but we still have to look at thermal comfort.

3.1. Results for thermal comfort

As explained before, we focused on the building operative temperature as thermal comfort indicator. With a set-point temperature fixed to 20°C, we are out of the comfort zone below 19°C or over 21°C. Results obtained for the month of January are presented figures 4 and 5. Mean operative temperatures are represented with their variation intervals, so that we can notice that :

- In average, load shedding hours are slightly uncomfortable
- In average, other hours of the days are comfortable

Repartition of comfort level for occupants for the two load shedding strategies are presented on the tables below :

Table 2. Thermal comfort levels repartition for simple load shedding strategy

	Simple load shedding		
Comfort level / Models	Simple	Enriched	Complex
Comfortable	100%	98,3%	99,2%
Slightly uncomfortable	0%	1,7%	0,8%
Uncomfortable	0%	0%	0%

Table 3. Thermal comfort levels repartition for load shedding after over-heating strategy

	Load shedding after over-heating		
Comfort level / Models	Simple	Enriched	Complex
Comfortable	98,5%	96%	100%
Slightly uncomfortable	1,5%	3,6%	0%
Uncomfortable	0%	0,4%	0%

Most of hours are still "comfortable" and that "uncomfortable" level is rarely reached. However, further studies on the impact of heating systems or on the perception of this comfort could be needed to consolidate these results.

Paradoxically, more discomfort is generated in the case of the complex strategy including over-heating. This can be explained by the fact that the two strategies are not considered for the same time slot, so that internal gains and external temperatures are not the same. From this observation, we can conclude that each time slot should be considered individually for further studies in the entire district impact.

3.2. Results for CO_2 emissions reduction

It is very common to conclude that CO_2 emissions will obviously decrease with load shedding strategies, when energy saving rates are positive. However, the energy savings rate should be put in perspective, as they only represent savings in regard to cut off energy. Therefore the energy savings on the entire day is much lower than ES_{rate}, so that with this logic daily CO_2 emissions reduction would be lowered too. Nevertheless, this does not prevent us to expect that CO_2 emissions would decrease as much as daily consumption.

To examine deeper the impact on district carbon footprint, it is crucial to consider the daily and intra-day CO_2 emission variability for the electrical production system. Thus, moving electrical consumption from a time period to another one could increase the CO_2 emissions, when local peaks don't match to global electrical system ones.

In the tables below are presented the mean ES_{rate} during January, the total consumption and CO_2 reductions during the entire month (respectively $Load_{red}$ and $CO_{2_{red}}$) and the expected gains reduction (EG_{red}), such as :

$$EG_{red} = \frac{Load_{red} - CO_{2_{red}}}{Load_{red}} \tag{4}$$

Table 4. Consumption and CO_2 emissions reduction during January for simple load shedding strategy

	Simple load shedding		
Models	Simple	Enriched	Complex
ES_{rate}	-10,0%	13,1%	5,5%
Total consumption reduction	0,40%	0,50%	0,22%
Total CO_2 emissions reduction	0,38%	0,50%	0,16%
Expected gains reduction	3,2%	0,70%	28%

Table 5. Consumption and CO_2 emissions reduction during January for load shedding after over-heating strategy

	Load shedding after over-heating		
Models	Simple	Enriched	Complex
ES_{rate}	3,1%	2,1%	2,4%
Total consumption reduction	0,21%	0,22%	0,14%
Total CO_2 emissions reduction	0,01%	0,05%	-0,06%
Expected gains reduction	94%	76%	144%

For the load shedding between 7am and 8am, the intuition is confirmed since the overall consumption reduction lead to reduction of the CO_2 emissions, though a little less as expected. However, for the second strategy with overheating, CO_2 emissions reduction is not so obvious anymore. Depending on the models, we can reduce from 76% less than expected to increasing the CO_2 emissions by transferring a load from a low-CO_2 emissions time slot to higher CO_2 emissions times of day. In order to be consistent with energy transition strategies, it is important to consider this aspect into load shedding impact evaluation to avoid a local amelioration to the detriment of general interest.

4. Discussion

With often few data available at district scale, statistical data base could provide good model enrichment in order to provide coherent load shedding impacts results, in respect to those available with detailed thermal simulation models. However, a comparison between simulation results and measurements would be necessary to validate the accuracy of the results, although it was unfortunately impossible to realize it with the experimental data by lack of data on the considered buildings and external factor as occupation schedules and weather data.

A further work will consist in implement the reduced thermal models together with generation parameters tools into an optimization library. This optimization point of view could allow stakeholders such as DSOs to define the best load shedding sequences into a district in order to maximize peak-shaving, while minimizing both the occupants' thermal discomfort and CO_2 emissions.

5. Conclusions

Cutting the heating load during one hour building by building in an entire district seem to be efficient for peak-shaving as the transfered load is very diffuse. Indeed, the rebound effects of the

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previous buildings do not cancel the peak reduction obtained by the current load shedding, which is crucial in the case of a long peak (more than an hour). However, thermal comfort can be reduced during theses load-shedding hours. The different models used do not allow us to estimate precisely how much and how it will be perceived by occupants, but help the stakeholder to know that it can be an issue. One solution could be to reduce heat loads instead of cutting them or cutting during shorter durations. Moreover, for CO_2 emissions reduction, estimation cannot be based only on consumption reduction as CO_2 emissions for electrical systems have dynamic variations that have to be taken into account.

Finally, the modeling approach will depend on the accuracy required, the data available and the time for the study design, so that it may be needed to mix modeling approaches for a study at district scale.

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Abbreviations

The following abbreviations are used in this manuscript:

COP21: 21th Conference of the Parties
CSTB: French Scientific and Technical Center for Building
DSO: Distribution System Operator
GEG: Grenoble Gas and Electricity
RTE: French transmission system operator
TEASER: Tool for Energy Analysis and Simulation for Efficient Retrofit
TSO: Transmission System Operator
UNFCCC: United Nations Framework Convention on Climate Change

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