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► To cite this version:

Marc Clausse, Frédéric Lefèvre, Yoann Jovet, Antoine Fontaine, Laurence Rocher, et al.. River water heat pumps to decarbonise district heating and promote the resilience of hydrosystems: Technico-economic, environmental and sociological challenges. *Energy Nexus*, 2024, 16, pp.100325. 10.1016/j.nexus.2024.100325 . hal-04743995

HAL Id: hal-04743995

<https://hal.science/hal-04743995v1>

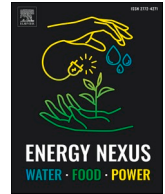
Submitted on 18 Oct 2024

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River water heat pumps to decarbonise district heating and promote the resilience of hydrosystems: Technico-economic, environmental and sociological challenges

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ARTICLE INFO

Keywords:

River water heat pump
Impact assessment
Techno-economic analysis
LCA, Sociological impact
Biodiversity
River thermal pollution
Water river rejection management
Aquatic ecosystem thermal response

ABSTRACT

The interdependence between water and energy (water-energy nexus) has been identified as one of the major challenges at European level, with roadmaps calling for the development of integrated approaches in this sector. The increase in river temperature is at the heart of this nexus, with anthropogenic thermal pollution adding to the effect of global warming. River Water Heat Pumps can play a major role by decarbonising district heating network (DHN) while actively cooling the aquatic resource. Hence, the objective of this short communication is to identify the scientific challenges to be met and the progress to be achieved considering the current state of the art. To illustrate the point, a rapid evaluation of the potential is performed for the city of Lyon in France resulting in an achievable cooling of ~ 1.5 K which is above the minimum threshold to see an effect on aquatic ecosystem while the CO₂ savings are significant for the DHN (\sim divided by a factor of 10). Because of its holistic nature, the impact assessment of such a system implies considering a wide diversity of indicators: energy, environmental, economics and sociological that need to be appropriately defined and quantified. In each field, progress beyond the state of the art to be performed has been identified, e.g. 4E analysis, cold water plume dispersion, integration of biodiversity in LCA.

1. Introduction

The interdependence between water and energy (water-energy nexus) has been identified as one of the major challenges at European level, with roadmaps calling for the development of integrated approaches in this sector [1]. The increase in river temperature is at the heart of this nexus, with anthropogenic thermal pollution adding to the impact of global warming, the effect of which on river temperature profiles has been highlighted by [2] for example. These temperature changes - particularly increases - have a strong impact on biodiversity and on the functioning of aquatic ecosystems [3]. The search for engineering solutions to ameliorate changing conditions by reducing river temperatures to support persistence of biodiversity is a major challenge, since conservation or restoration to the previous state are difficult to achieve [4].

Among these engineering solutions, the development of urban heat networks using heat pumps (HP) connected to an aquatic resource (river, groundwater, reservoir) is a novel solution contributing to the resilience of ecosystems, firstly by limiting the impacts (carbon and pollutant emissions), but also actively by cooling the aquatic resource (Fig. 1). The idea is effectively to release water, from which heat has been recovered, into the riverine ecosystem, thus reducing the thermal stress linked to global warming or other anthropogenic activities [5]. However, the sustainability of this solution depends on the associated environmental impacts beyond the simple climate change indicator [6], and the consequences on urban sociology. For example, this last aspect was extensively discussed by Correljé et al. [7] in their recent paper. They stressed out the transition towards sustainable urban energy systems demands more than mere technological innovation, pointing out the multiple needed research activities in institutions and governance,

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<https://doi.org/10.1016/j.nexus.2024.100325>

Received 21 December 2023; Received in revised form 19 July 2024; Accepted 12 September 2024

Available online 12 September 2024

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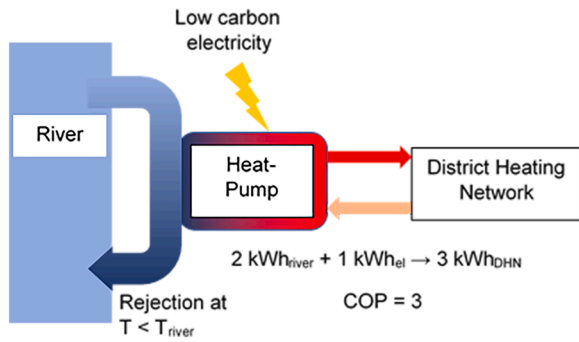


Fig. 1. River water heat pump working principle.

values and social acceptance or citizen involvement.

Hence, characterising a District Heating Network (DHN) interconnected to river water taking into account technical-economic, environmental and sociological criteria implies to:

1. Quantify the energy efficiency and environmental impacts of replacing traditional heat generators (mainly gas and biomass boilers, incinerators) with a river water heat pump solution,
2. Characterise the possibilities of cooling river water, especially in relation to the discharge strategy (geometry, position, flow rate) of the cooled water,

3. Quantify the positive effect of an artificially controlled temperature decrease on the functioning of aquatic ecosystems, for instance by using bioindicators as aquatic plant communities,
4. Study the sociological consequences on a city scale of the deployment of these solutions and their integration within existing technical systems and networks of actors.

The existence of positive externalities (impact on river biodiversity and functioning, impact on citizens) beyond heat decarbonation due to replacement of existing heat generation systems by river heat pumps, is the main driver of implementing these systems. However, a trade-off has to be found between opposite goals as the minimisation of all indicators: energy consumption, environmental impacts, economical cost and social impact, etc. at the same time is not realistic. To identify the best compromises, a holistic interdisciplinary approach is required and this article aims at identifying and discussing the main challenges to be met.

2. Potential impact of river heat pump deployment

Because of the holistic nature of such a system, the quantification of the expected results is challenging per se. To set up the scene, preliminary calculations have been run for the Grand Lyon Metropole (France, 1.4 million inhabitants) district heating (DH). As shown in Fig. 2, significant extension of the network is already foreseen and accesses to the river resources are numerous and close to a wide variety of end-users. Furthermore, the heat generation mix consists of gas units,

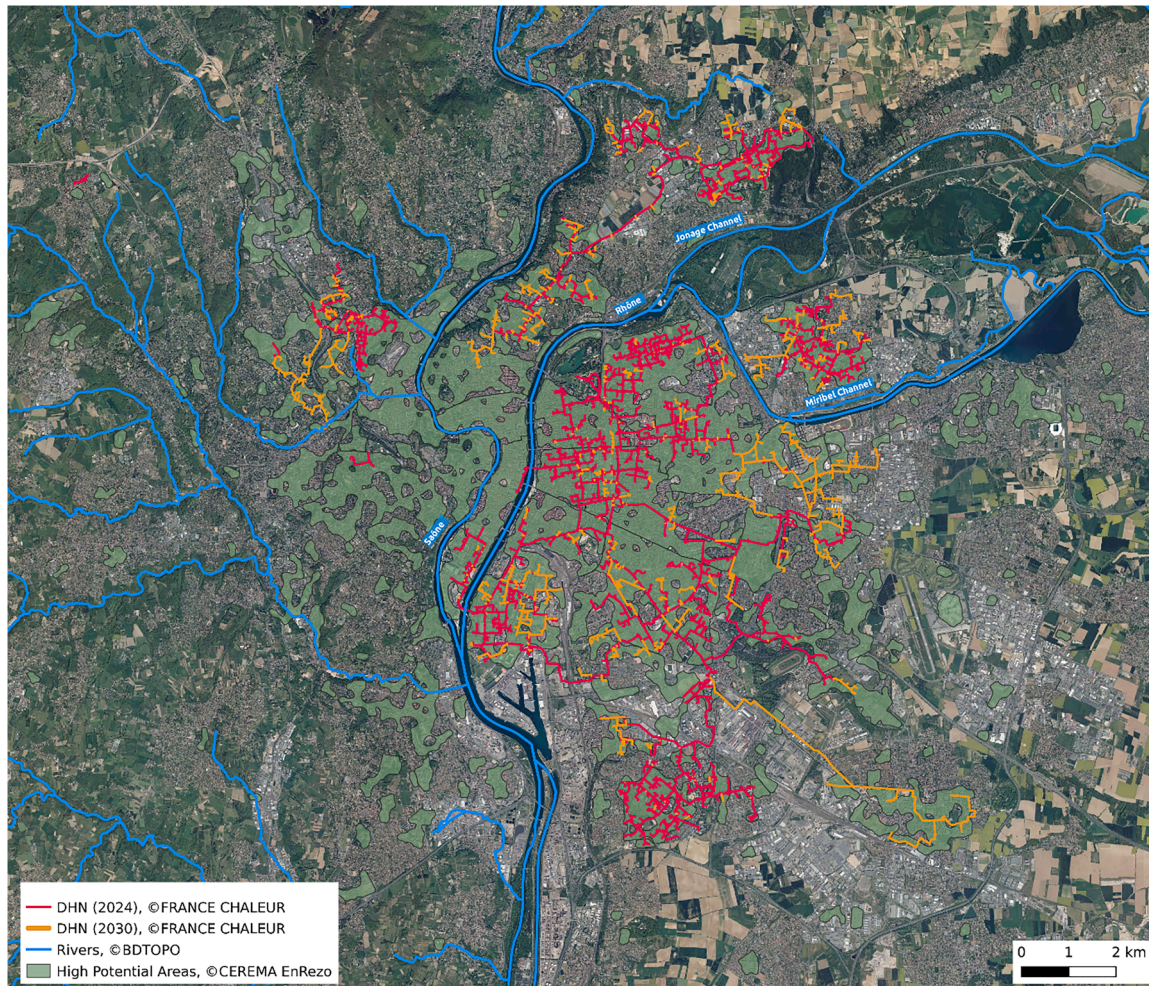


Fig. 2. Evolution of the Lyon Centre Metropole DHN (red 2015, orange goal for 2030), high potential areas for DHN extension beyond 2030 (green zone) and main river resources [9].

fuel units for back-up, biomass and incinerators; the last two ones representing 65 % of the total production at the 2027 horizon [8].

Considering the existing and foreseen heating demand (table 1), significant cooling of river flows can be achieved (from 0.5 K to 1.5 K or more with adequate rejection strategy) depending on the integration strategy. With adequate sizing of heat pumps and seasonal thermal storage, a full replacement of existing solution can credibly be achieved considering installations in other countries [10]. Hence massive decarbonation could be achieved, the average carbon content in DH falling from 107 g/kWh [11] to about 12–15 g/kWh, assuming a Coefficient of Performance (COP) of 3 for the heat pump and an electricity carbon content of 35–45 g/kWh_{el} for France. However, this highly significant carbon emission reduction must be balanced against other impacts (environmental, sociologic, economic) to define the best configurations.

As for biodiversity, considering the targeted temperature decrease, a decrease of the level of stress for cold water species and changes in the relative abundance of species having different thermal preferences is expected [13–15]. The benefit of river cooling has been highlighted in several studies like in Seedang et al. [16] who discussed the impact of a reduction in temperature between 0.48 and 1.99 °C on ecosystem restoration. Abdi et al. [5] have shown positive effect on river dissolved oxygen (DO) for cooling as low as 0.3 – 0.7 °C, the effect increasing significantly for greater variations in temperature (value as high as 7 °C were tested). As stated by these authors, this improvement in DO saturation level leads to a better habitat for “desired fish and other aquatic organisms”.

3. Scientific and technical barriers

Because of the required holistic approach, the barriers are numerous and related to several research field. The main ones are discussed hereafter.

3.1. River heat pump based DHN design, simulation and assessment

The impact assessment of river water heat pumps remains relatively unexplored to date, despite their definite potential to decarbonise heat production in urban areas [17–18]. Moreover, the studies carried out are mostly limited to technical (mostly energy [12], but also exergy analysis) even in some very recent studies [19]. In case of multicriteria based analysis, energy analysis is complemented by economic indicators coupled with an evaluation of gains in CO₂ emissions, e.g. [17],[20], [21],[22], without implementing a complete LCA (Life Cycle Assessment) approach based on the full set of impact categories (definition in appendix), while it has been proven highly necessary in similar cases (industrial heat) to obtain a fair comparison [23]. Indeed, although 4E (Energy, Exergy, Economic and Environmental) assessment is increasingly used, no generic tool is currently available to perform such an

Table 1

River temperature decrease for different locations of cool water release in Lyon centre Metropole (France) and heat demand assuming a COP of 3 for heat-pumps [12].

		Rivers to be equipped		
		Saône (annual average)	Saône (low-water average 5 months)	Channel of Miribel
Flow rate (m ³ /s)		473	224	30
Achieved	Reference	0.02	0.12	0.37
ΔT (K)	demand (615 GWh)			
	Extension 2030 (1678 GWh)	0.06	0.33	1.01
	Lyon all DHN 2030 (2425 GWh)	0.09	0.47	1.47

analysis. Hence, specific modelling needs to be performed and appropriate scenarios defined. Furthermore, a truly relevant assessment of the sustainability of the available solutions requires positioning them in relation to global limits, which must be transcribed at the level of the concerned sector [24].

Finally, in the context of new metropolitan heating strategy deployment, important attention should be paid to the integration of the studied solution in the local energy system, understood as an intertwined set of infrastructures, public policies and energy practices [25]. Indeed, under the effect of European and French public energy policies, the energy mix of heat provision is rapidly diversifying and new energy sources are being integrated. This is particularly the case for waste heat, whether it is generated by industrial actors or urban services [26],[27]. However, the construction of systematic heat policies still lacks recognition [28]. Within a framework of urban political ecology [29], how new ways of producing heat and heating renew urban configurations have to be questioned. Compared to recent research [30], a strong focus on the water-energy nexus is needed to question adequately the social, political, economic, legal, and geographical relationships at play in the mobilization of urban waterways as a decarbonized energy resource.

3.2. Cooling the river and its impact on the aquatic ecosystems

The impact of a thermal stress is conditioned, among other, by the response of organisms. This implies knowing, on different time scales, the effect of seasonal temperature changes [31], on the thermal decrease needed to create cool shelters for organisms (impact on physiology and growth [32], balance between species [33], indicators of ecosystem's health [34]). The impact on the organisms is also conditioned by the achievable temperature reductions, through the dispersion of cooled water within the river. A given cool-water outflow can have different effects: its slow dispersion within the river favours the cooling of a selected river bank over a long distance, while a fast dispersion cools the whole river section, far-less intensively. Understanding the dispersion of a fresh-water plume is thus paramount, notably the influence of buoyancy and stratification [35], the discharge strategy [36] and the interaction of the plume with the canopy [37,38], – at the frontier of biology and hydrodynamics.

Hence two strategies of fresh water dispersion can be considered. A first strategy is to promote a rapid mixing of the fresh water, causing a global cooling of the river. It requires an efficient mixing directly at the exhaust, either making profit of local turbulence [39] or using dedicated mixing devices [40]. The other strategy is a limited thermal mixing of the fresh water with the river flow in order to form local thermal refugia in privileged regions of the river, with a more pronounced temperature decrease [41]. Thermal effluents are subject to buoyancy effects: the injected cool water is heavier than the river water, and temperature gradients affect the mixing. A stable stratification is known to reduce vertical motions by causing density and stratification effects [42,43]. Classical criteria to predict this stratification, like a Richardson number successfully used in tidal estuaries, are inadequate for river applications [43]. Hence, the dynamics of a cooler (negatively buoyant) flow along an inclined bank remains a scientific gap [44] that needs to be filled by detailing the plume dispersion, conditions of stratification (plume plunging towards the river bed, below the banks) in relation with non-dimensional parameters (e.g. Richardson number, river to effluent flow-rate ratio).

The privileged regions to be cooled to form thermal refugia are in the near surface photic region (depth usually <2 m) where the river banks are colonised by aquatic plants used as habitat by many species. Such a plant canopy acts as a porous region which affects the hydrodynamics and the local mixing due to both a reduced velocity [45] and large coherent structures generated at the interface with the main-stream [37]. With the increase of computational capacities, eddy resolving computational methods as Large-Eddy Simulation (LES) or Detached Eddy Simulation (DES), have become an affordable and efficient tool for

Table 2
State of the art vs. progress to be achieved.

State of the Art	Progress to be achieved
Assessment of DHN performance for one configuration, based on thermo-economic approach plus CO ₂ balance	Full 4E (energy, exergy, economic & environment) assessment for various configurations and evolutions in time with consequential LCA in case of massive impact on Country's grid
Impact of seasonal storage evaluated mainly for solar DHN	Evaluation of seasonal storage benefit for river water heat pumps based DHN
SSH approach mostly limited to economic aspects or to the construction of social acceptance	Social, environmental, economic, political and technical issues taken altogether in the context of a socio-technical sciences analysis
River mixing phenomenon mainly characterised for positive buoyant plume	Better understanding of cold water plume dispersion and stratification conditions
River flow modelled without canopy interaction most of the time	River flows with the presence of aquatic plants and canopy on river banks modelled with LES
No consensus on indicators or methods have been established to integrate the biodiversity into LCA	Multi scale approach (from physiology to community) based on key organisms, as aquatic vegetation, to integrate functional assessment of the biodiversity into LCA.
Lack of integrative study on responses of aquatic plant community to changes in temperature	Quantification of key processes (stress, productivity, phenology, species interaction) to provide comprehensive assessment of responses of aquatic vegetation
Lack of study of the possible resilience of aquatic communities in case of water refreshing	Quantification of the responses of aquatic communities to water refreshing, and hence of the resilience capacity, step necessary to propose restoration and nature-based solutions to global warming

flow prediction at large scales [46] and in rivers [47]. Using these methods, instantaneous large scales of the turbulent river flow are resolved, while scales smaller than the grid, called subgrid scales are modelled with promising results for similar configurations [44]. The eddy resolving methods proved their efficiency for characterizing the mixing of cool water at the scale of the city reach, up to a few kilometres [48,49]. Nevertheless, a specific challenge is to reproduce at the same time small-scale (near-field of the outflow) and large-scale (of the river reach) thermal mixing with affordable meshing efforts and CPU time.

3.3. Biodiversity in LCA (Life cycle assessment)

As highlighted in the 2019 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services report [50] or in recent publications [51], the inclusion of biodiversity in LCA remains a challenge. Indeed, it has been until now limited to specific species or is considered in related factors such as climate change or land use; even if several authors have discussed options to incorporate ecosystem services, they remain limited so far. There is therefore a strong issue at stake regarding these questions for LCA.

In aquatic ecosystems, plants play key roles on both other biological groups (macroinvertebrates, fish, etc.) and ecosystem functioning

(shelter and food for animals, water oxygenation, nutrient cycling, sediment formation, erosion regulation etc. [52,53]). Still, plants being fixed, they respond strongly to local environmental conditions [54], and are thus commonly used as bioindicators of ecosystem functioning and health [34]. Using aquatic plant communities for assessment of the effect of water refreshing and implementation of LCA could enable both to characterize finely the effects of changes in water temperature on living organisms through responses of individual plants and to assess consequences on ecosystem functioning [55]. Responses of aquatic plant to changes in temperature have mostly been studied in the sense of increased temperature due to global warming [56],[57], with reported effect at different levels: plant physiology and growth, species distribution and species interactions [31]. When plants are subjected to unfavourable conditions of temperature, cell metabolism produces Reactive Oxygen Species (ROS) which can then be used as an indicator of the level of stress [58]. At the individual plant level, the water temperature strongly influences productivity, phenology (e.g. leaf bud burst, flowering) and growth [59],[13],[31]. At the community level, changes in temperature leads to changes in frequency and abundance of species having different thermal preferences [13],[15]. The plant response will depend on the initial water temperature, the amplitude of water cooling and on the thermal preference of the considered species. Measuring the response to water refreshing of a large set of species having contrasting thermal preferences would permit to characterize the responses of the ecosystems, integrating its complexity as an expected "beneficial" effect for cold-water species vs. a "negative" effect on thermal tolerant species as invasive species.

Though a large number of attempts has been made to integrate the biodiversity into LCA, there is still no consensus on indicators or methods due to the complexity of the biodiversity and ecosystems [51],[60]. In many cases, going beyond a simple assessment of species richness and integrating functional assessment is crucial to characterize the pressure on biodiversity and ecosystems in a relevant way [61].

4. Conclusion

The aim of this article is to discuss the scientific challenges that need to be met to better assess the impact of district heating decarbonation through the deployment of River Water Heat-Pumps.

The literature review and discussion confirm these challenges are many and diverse. In consequence, a strong interdisciplinary approach is required to address them appropriately combining aquatic biology, flow mechanics, energy engineering sciences, social sciences, etc.

To highlight the diversity of the challenges, the actual state of the art on the subject and the progress that needs to be achieved, are summarised in Table 2 for the sake of clarity.

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.

APPENDIX

Life Cycle Impact Assessment. The impact categories, classification and characterisation used in EF 3.0 methodology developed with the Join Research Center from European commission for the environmental analyses [62] are presented in Table A1.

Table A1
Environmental and energy Impact categories with description from SIMAPRO software.

Source	Impact category	Units	Description
EF 3.0	Climate change	kg CO2 eq	Radiative forcing as Global Warming Potential GWP100 Baseline model of the IPCC 2013 with some factors adapted from EF guidance
	Ozone depletion	kg CFC11 eq	Ozone Depletion Potential calculating the destructive effects on the stratospheric ozone layer over a time horizon of 100 years.
	Ionising radiation	kBq U-235 eq	Ionizing Radiation Potentials: Quantification of the impact of ionizing radiation on the population, in comparison to Uranium 235.
	Photochemical ozone formation	kg NMVOC eq	Expression of the potential contribution to photochemical ozone formation.
	Particulate matter	disease incidence	Disease incidence due to kg of PM2.5 emitted. The indicator is calculated applying the average slope between the Emission Response Function (ERF) working point and the theoretical minimum-risk level. Exposure model based on archetypes that include urban environments, rural environments, and indoor environments within urban and rural areas.
	Human toxicity, non-cancer	CTUh	Comparative Toxic Unit for human. Using USEtox consensus multimedia model. It spans two spatial scales: continental scale consisting of six compartments (urban air, rural air, agricultural soil, natural soil, freshwater and coastal marine water), and the global scale with the same structure but without the urban air.
	Human toxicity, cancer	CTUh	Comparative Toxic Unit for human. Using USEtox consensus multimedia model. It spans two spatial scales: continental scale consisting of six compartments (urban air, rural air, agricultural soil, natural soil, freshwater and coastal marine water), and the global scale with the same structure but without the urban air.
	Acidification	mol H+ eq	Accumulated Exceedance characterising the change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit.
	Eutrophication, freshwater	kg P eq	Nitrogen equivalents: Expression of the degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as limiting factor in marine water).
	Eutrophication, marine	kg N eq	Nitrogen equivalents: Expression of the degree to which the emitted nutrients reach the marine end compartment (nitrogen considered as limiting factor in marine water).
	Eutrophication, terrestrial	mol N eq	Accumulated Exceedance characterising the change in critical load exceedance of the sensitive area, to which eutrophying substances deposit.
	Ecotoxicity, freshwater	CTUe	Comparative Toxic Unit for ecosystems. Using USEtox consensus multimedia model. It spans two spatial scales: continental scale consisting of six compartments (urban air, rural air, agricultural soil, natural soil, freshwater and coastal marine water), and the global scale with the same structure but without the urban air.
	Land use	Pt	Soil quality index Calculated by JRC starting from LANCA® v 2.2 as baseline model.
	Ecoinvent	Water use	m3 deprivation
Resource use, fossils		MJ	Abiotic resource depletion fossil fuels; based on lower heating value ADP for energy carriers, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016).
Resource use, minerals and metals		kg Sb eq	Abiotic resource depletion (ADP ultimate reserve) ADP for mineral and metal resources, based on van Oers et al. 2002 as implemented in CML, v. 4.8 (2016).
Cumulative energy demand		MJ	Method to calculate Cumulative Energy Demand (CED), based on the method published by Ecoinvent version 2.0 and expanded by PRé Consultants for raw materials available in the Simapro 7 database. The method is based on higher heating values (HHV)
Cumulative exergy demand		MJ	In this method exergy is used as a measure of the potential loss of "useful" energy resources.

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