HARVARD SUMMER SCHOOL

Biologically Inspired Innovation

HARNESSING THE SEINE

HARVARD
UNIVERSITY

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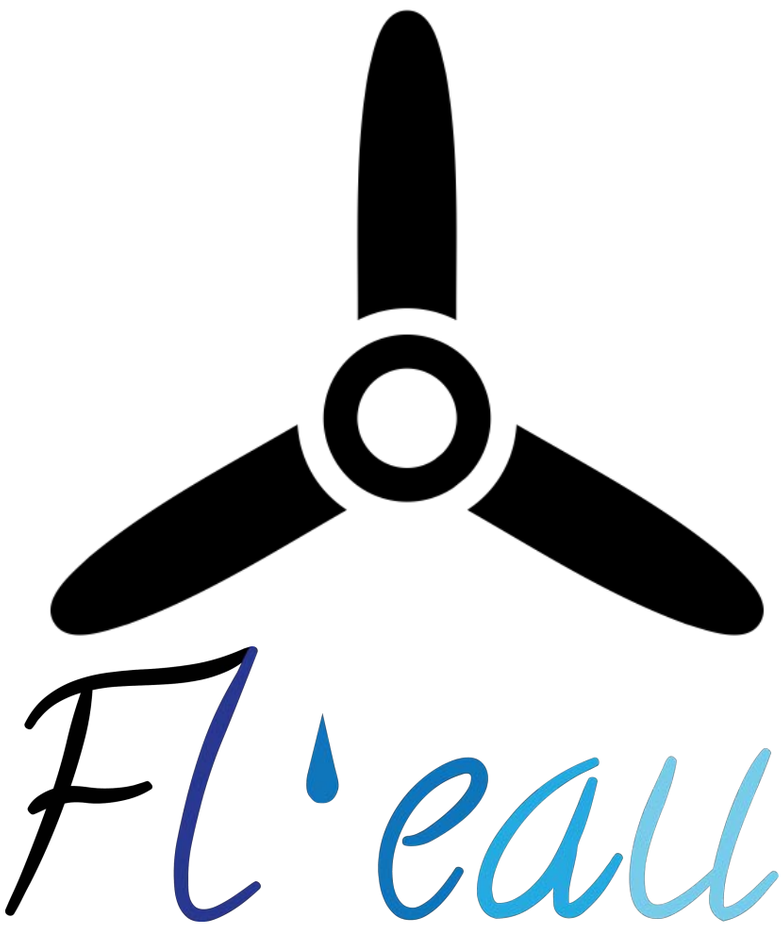
HARVARD SUMMER SCHOOL

Biology and the evolution of Paris as a Smart City

ABSTRACT



Concept Logo for our Project
Designed by Harvard Summer School

The Seine is one of the most beautiful sites in Paris, and our project seeks to capitalize on the strength that lies just under the surface of this majestic river. Inspired by the mechanism of the ATP synthase enzyme, we propose the installation of hydroelectric kinetic turbines on the bed of the Seine to generate a sustainable source of electricity. This electricity will then be used to help power the RATP subway system, a vital part of Parisian life utilized by over one-and-a-half billion people each year. France has a history of involvement in sustainable energy, and while many cities have integrated hydroelectric turbines into their rivers, our proposal is the first to link this generated energy to a public transportation system. *Fl'eau* promises to positively impact an integral component of Paris's transportation network by supplying it with a sustainable source of energy, thereby creating jobs and recentralizing energy production in the city of Paris itself.

TABLE OF CONTENTS

The Potential of the Seine

Each year, over one-and-a-half billion people ride the métro and RER in Paris.[1] This network of public transportation forms the foundation for commute in and around the city and serves as a fundamental cultural characteristic of Paris as well. The metro itself opened on 19 July 1900 in order to provide transportation for the Olympic Games and in 1998, the Métro Ligne 14 became the first metro line in a major city to have no driver.[2] Today, the RATP (Régie Autonome des Transports Parisiens) network consists of 220 km of rail lines and services 383 stations.[3] Each train that travels these tracks is powered with a third-rail system, meaning that the entirety of the network is electrically powered. While this, of course, means that the trains are not emitting greenhouse gases as they traverse the tunnels of Paris, there is still a staggering amount of energy being consumed. The electricity used by the RATP network is primarily produced via coal and nuclear power, and these plants reside far beyond the borders of the city itself.

That said, the use of a public transit system replaces the automobile as the primary mode of travel, which in turns contributes to the smaller carbon footprint of city residents as compared to rural residents.[4] Given the use of electricity instead of gasoline in such an integral system of transportation in Paris, can further substantial improvements be made to Paris's energy consumption and carbon footprint?

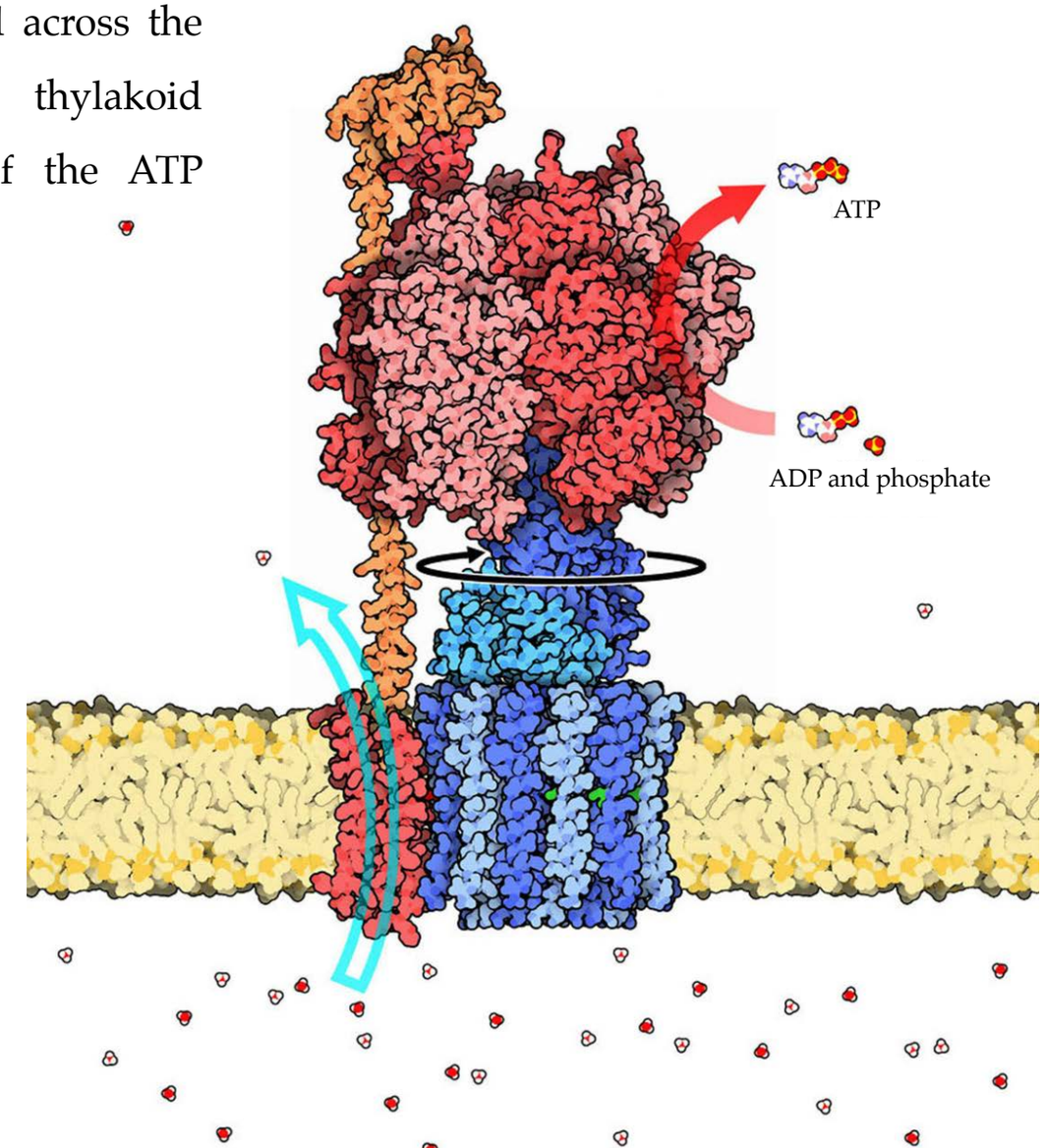
A Young Parisian entering the Châtelet Métro station

We firmly respond *oui*. Paris, and France as a whole, have long been committed to sustainable sources of energy; this is well represented by France's use of nuclear energy as a means of generating electricity. Approximately 75% of France's electricity is generated using nuclear energy, and France is the world's leading exporter of electricity as a direct result of the low cost of its generation.[5]

This spirit of dedication to clean energy can carry Paris into a new chapter of sustainable public transportation and responsible resource usage. By installing hydroelectric turbines in the bed of the Seine River, electricity may be generated from the kinetic energy presented by the flow of the river itself. As fluid dynamics follows the physical laws of Newtonian mechanics as a whole, certain principles may be exploited to maximize the potential for energy conversion.[6]

The flow of water in the Seine would best be categorized as a laminar steady flow, meaning that the water in the river flows without significant turbulence or randomness.[7,8] This consistency in fluid momentum is highly conducive to the nature of our proposal, as it provides a reliable source of mechanical energy which may then be converted, using a hydroelectric turbine, into electrical energy.

In considering this energy challenge, it is beneficial to employ the conceptual analogy of the City as a living Organism. The cell has evolved over millions of years through selective pressures, so its mechanisms have been well-tested. For this reason, we will use a biological parallel to inspire our approach to this foray into hydroelectric energy production. The aforementioned fluid flow in the Seine is analogous to the hydrogen ion gradient that is maintained across the inner mitochondrial or thylakoid membrane in the case of the ATP synthase.[9]



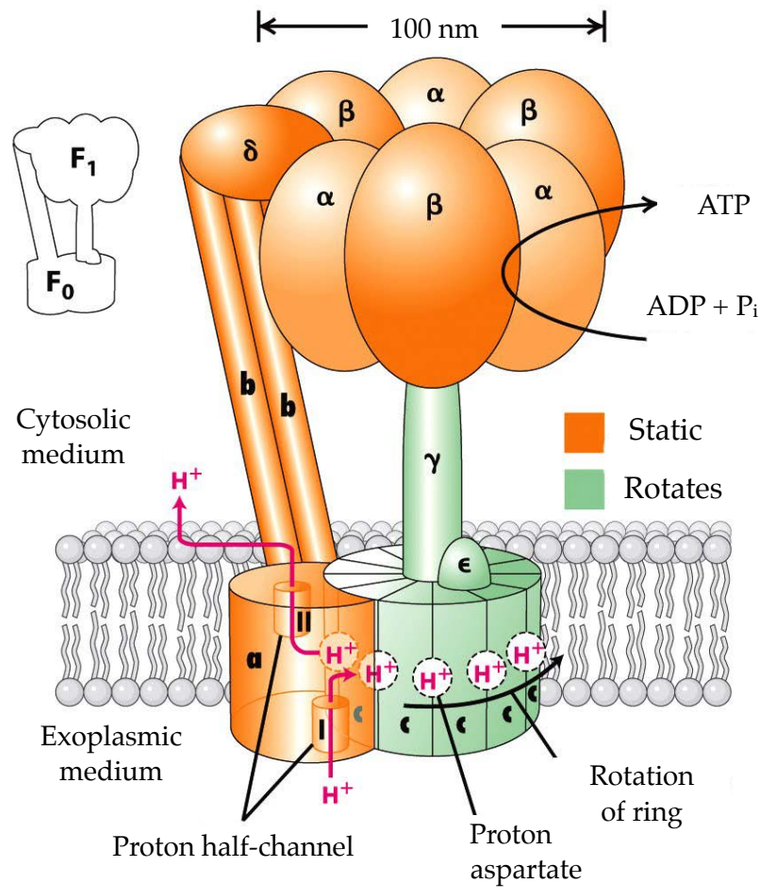
ATP Synthase enzyme shown across membrane

“Guided by the physical principles of fluid mechanics and the biological concepts illustrated by the ATP synthase, we are confident in this project’s potential to have a lasting impact on the citizens of Paris and the energetic sustainability of the city collectively.“

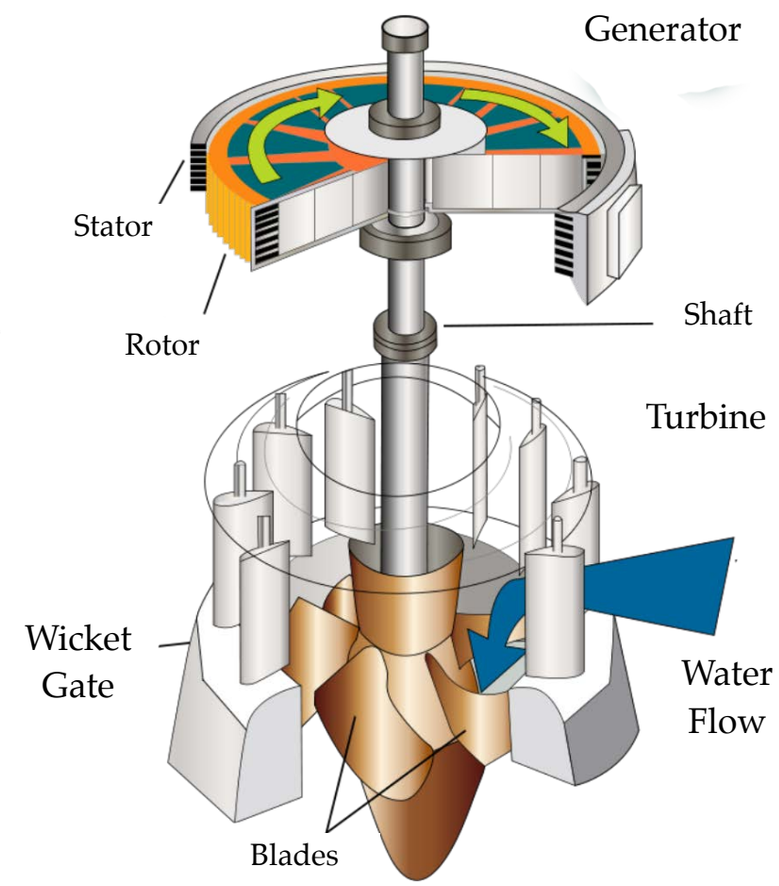
The ATP synthase is a highly intricate protein structure present in eukaryotic cells, and it performs a critical role in cell metabolism. The turbine in the synthase works by anabolizing ADP to ATP using inorganic phosphate and the energy generated by turbine rotation, and the turbine itself is powered by a chemical gradient of hydrogen protons. The osmotic flow of these protons are a form of potential energy that is transformed by the ATP synthase to generate ATP.

It is the single largest producer of cellular energy and is essential to life at the most basic level. Much like the synthase enzyme and its chemiosmotic potential energy, the hydroelectric turbines will have the relatively constant fluid momentum of the Seine to power their generators. We propose to install a series of hydroelectric kinetic turbines in the Seine River in order to create a source of sustainably generated electricity to provide power for the RATP network of subway trains. Guided by the physical principles of fluid mechanics and the biological concepts illustrated by the ATP synthase, we are confident in this project’s potential to have a lasting impact on the citizens of Paris and the energetic sustainability of the city collectively.

As can be seen in the figures to the right, the structural similarities between the mechanisms of the ATP synthase enzyme and the turbine-generator complex provide fodder not only for design inspiration, but also to enable the conceptualization of biophysical analogies that will enhance the impact of this proposed installation. By helping to supply the most vital transportation network of the city with energy, we are making an investment in the future of Paris that will have positive implications for generations to come.



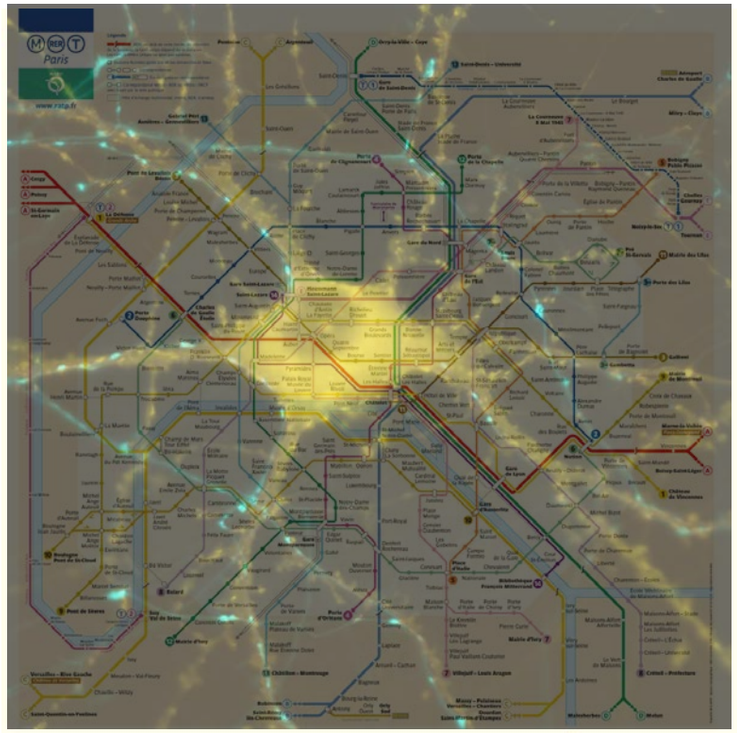
ATP Synthase Animated Depiction



Hydroelectric Turbine Schematic

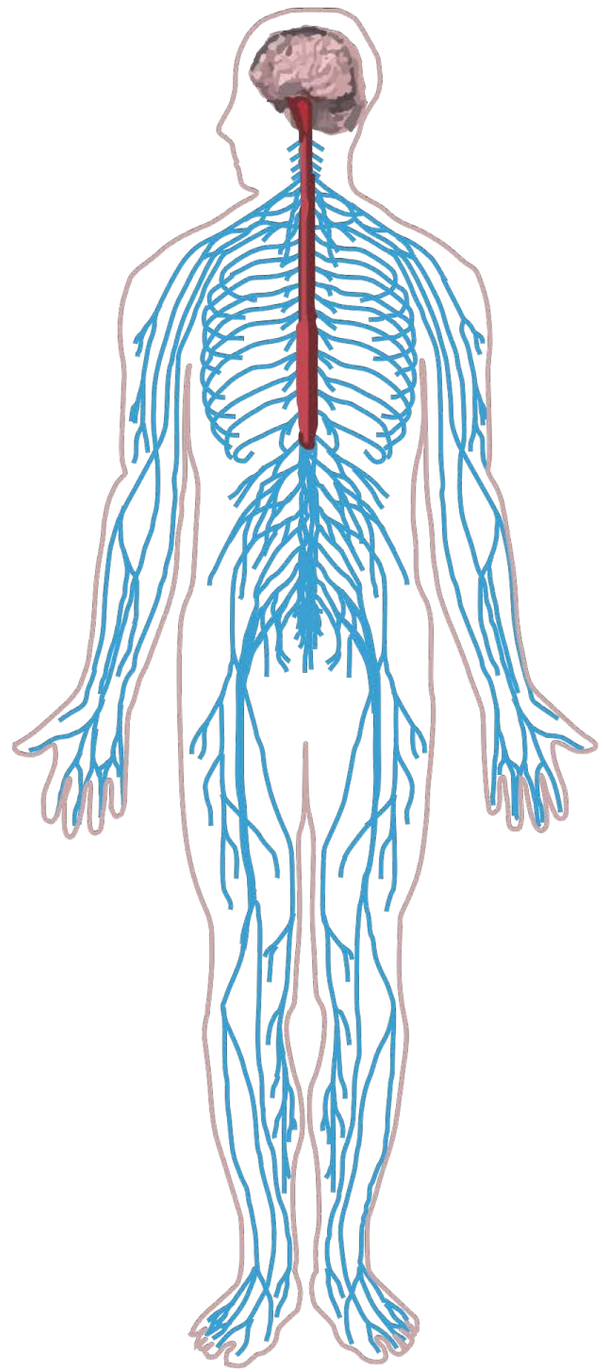
The Parisian Impact

If one examines a map of the RATP network in Paris, twelve of the underground lines are seen to cross the Seine at least one time.[10] This orthogonal intersection provides a logistically favorable opportunity[11] to connect the hydroelectric kinetic turbine generators with the electrical network that powers the third rail DC and overhead AC systems of the metro.[12] As the Seine intersects with so many rails, there are numerous opportunities for the installation of a power supply network. Integrating this source of renewable hydroelectric energy would reduce the utilization of electricity produced by the burning of coal. This dissemination of electricity at strategic locations in the rail network can be analogized to the nervous system of some mammals.



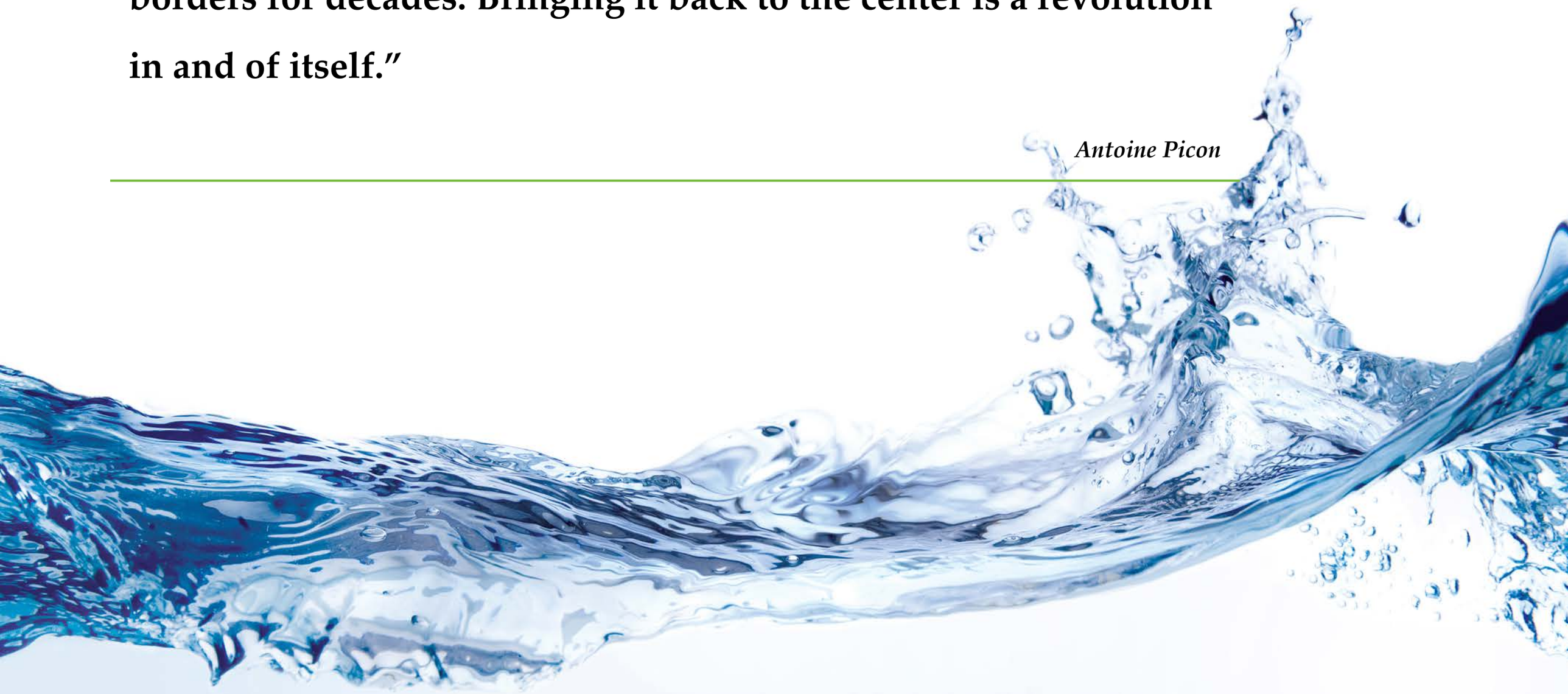
Nerve Cell overlaid on RATP map
Created by Harvard Summer School

We take humans as an example, as Homo sapiens is the species that most directly benefits from the presence of a functional rail network. In our proposed system, the Seine is analogous to the spinal cord, a critical piece of the central nervous system. Branching off of this bundle of nerves are, of course, a vast array of smaller, more highly differentiated nerve cells,[13] much in the same way that the rail system branches with increasing complexity as it moves away from the Seine. In this situation, the peripheral nervous system can be likened to the RATP lines that emanate from the intersections with the Seine. By installing hydroelectric generators at the nervous center of a system that spans the city as a whole, electricity may be dispensed in the most efficient manner and to the highest number of RATP rail lines.



"Cities have been moving energy production outside their borders for decades. Bringing it back to the center is a revolution in and of itself."

Antoine Picon

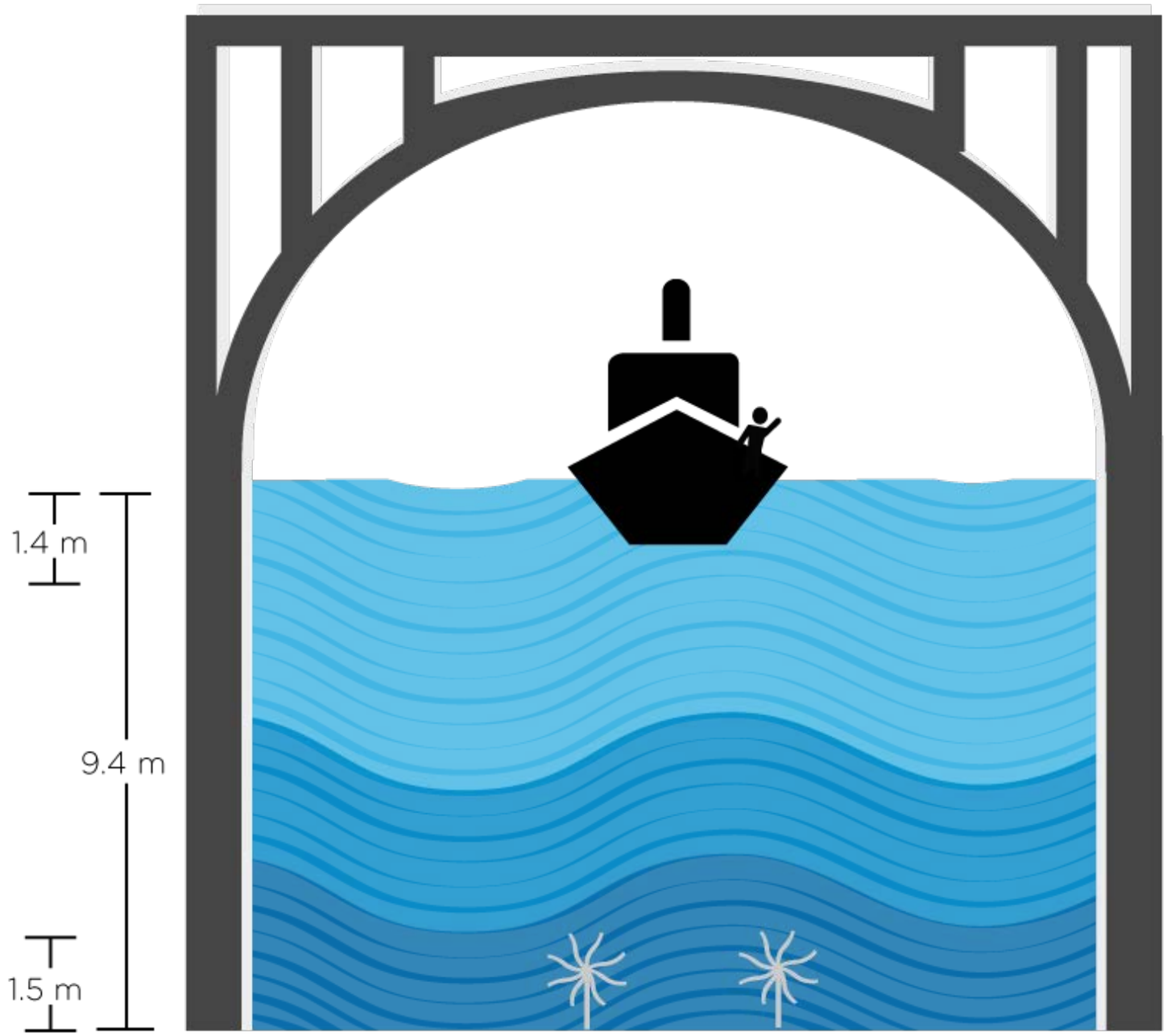


Returning to the human impact of this proposal, one must consider the repercussions of altering a system that is so vital to the everyday function of the urban biome of Paris. Installing these generators, while clearly beneficial when considering the long term sustainability of Paris, could be met with resistance by those commuters who heavily depend on the RATP for transportation, as the construction process could potentially involve intermittent service interruption. Even for those who do not use the subway frequently, there may be concern that the generators would mar the otherwise beautifully picturesque Seine. To address the first concern, the installation would have to take place in stages so as to minimize the interruption of rail service. The gravity of such a disturbance is seen in the upcoming closure of the RER A between La Défense and Auber.[14]

View of métro train interior and passengers

Since up to twelve lines would be affected by this proposal, very careful planning in the construction process is paramount. The relevant phases of construction will be discussed in the Execution Plan.

Fortunately, the second concern is more easily nullified. Unlike other types of kinetic turbines, like wind turbine generators, hydroelectric kinetic turbines must rest below the surface of the water,[15] so they would not be able to be seen by an onlooker or passerby. The impact on the aesthetics of the Seine, then, is minimal. And, given the relatively short height of each turbine,[16] as seen through the figure to the right, ferry tours of the Seine would not have to concern themselves with hitting these generators.



Cross-Sectional Diagram of Seine
Created by Harvard Summer School

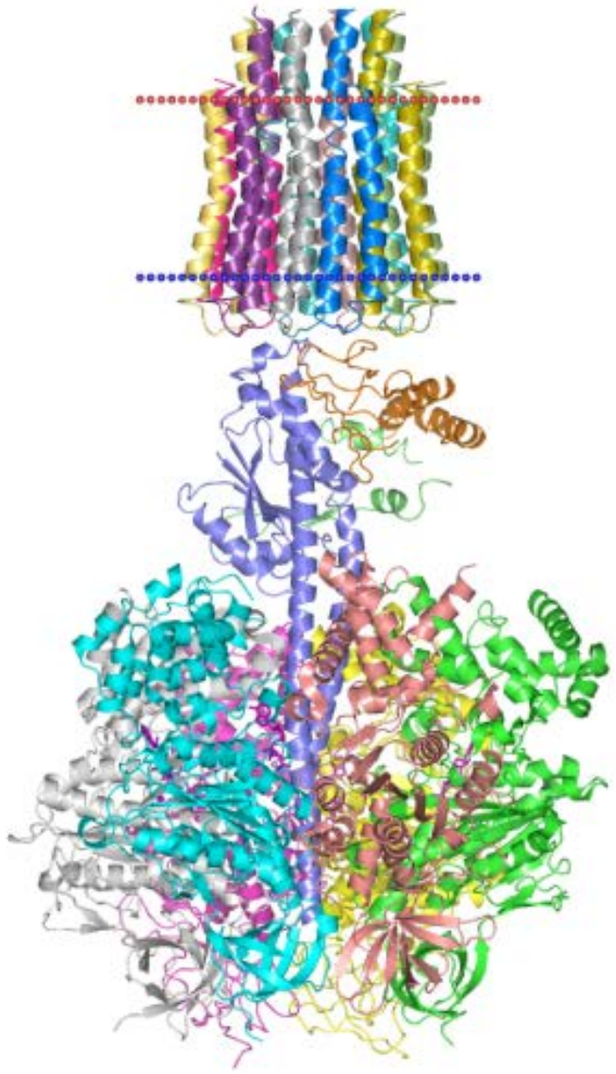
The nature of this proposal is intriguing in that, if it works as intended, the Parisian commuter of today will notice no change. The same amount of electricity will power the third rail, and that same third rail DC system will power the train that takes him or her to his or her respective destination. The target of our project, therefore, is the Parisian of tomorrow. We envision the implementation of this proposal reducing the need for fossil fuel consumption in order to power the RATP network, much as the autolib' strives to reduce automobile emissions.

Our model seeks to engage with the citizen of today in order to impact the citizen of tomorrow by using the technology available presently. The RATP network is accessible to all, be they rich, poor, well-educated, Parisian, tourist, immigrant. Our proposal reaches beyond not only the barriers of time, but has an impact regardless of race, creed, or socioeconomic status. No smart phone or internet connection is required, and no discrimination applies. This project continues a public service in the present while helping to ensure a healthier tomorrow for that same public to enjoy.

"Our proposal reaches beyond not only the barriers of time, but has an impact regardless of race, creed, or socioeconomic status."

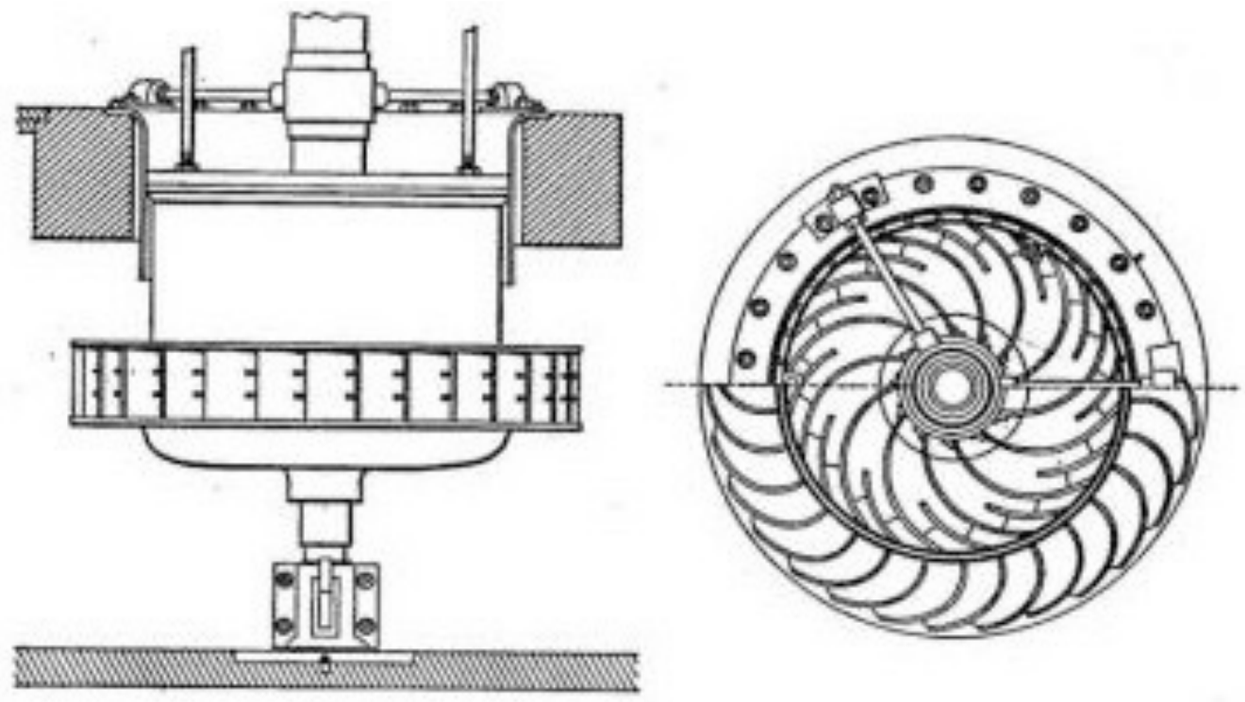
Learning from the Past

The ATP synthase is a remarkably complex enzyme that is a result of countless cycles of differentiation, selection, and evolution.[17] The current synthase structure is a machine that has near perfect efficiency,[18] a feat that is unimaginable in modern human engineering. The enzyme achieved this level of perfection as a result of constant improvement and innovation. In rethinking the ways in which we use hydroelectric power, the state of renewable energy may continue to develop, much in the same manner as the synthase was honed.



ATP Synthase Protein Structure

As previously mentioned, France has been active in its pursuit of responsibly and sustainably produced electricity, although this has primarily manifested itself in the forms of nuclear and wind energy.[19] In terms of water energy, harnessing the power of flowing fluid is not necessarily novel. For centuries, civilizations have settled around bodies of water for drinking, bathing, and agriculture, but the use of water in mechanics is relatively recent. The Chinese and Greeks used the power of rivers and falling water to grind wheat into flour roughly 2000 years ago. In the late eighteenth century, hydropower was used with water wheels to generate power for cotton mills.[20] In the nineteenth century, turbines began to be developed, the first in 1827 by Benoit Fourneyron, a French engineer. His turbine was capable of generating about 6 horsepower (roughly 4000 watts).[21] How fitting it is that the technology he pioneered has the potential to supply power to such a significant pillar of infrastructure in modern-day Paris.



Fourneyron Turbine

In 2012, New York City implemented a similar project, the Roosevelt Island Tidal Energy project, which aimed at installing 30 turbines along the East River in hopes of generating 1050 kilowatts of electricity to be delivered to the homes of 9500 New York City residents. This project, under the company Verdant Power, is the first tidal energy project licensed by the Federal Energy Regulatory Commission. Aimed to be completed in 2015, it promises to take advantage of more waterways to create energy for local inhabitants.

This project in the United States lends precedent to our proposal in that it uses the flow of the East River's current to generate hydroelectricity using kinetic turbines. This differs from most hydroelectric projects that use massive damming systems, and this key difference is what we hope to parallel in the Seine.

"What distinguishes *Fl'eau*, however, is that instead of producing electricity for the electric grid more generally, we are suggesting the direct integration of this electricity in the public transportation network."

Damming the Seine is non-optional from both a functional and aesthetic perspective, and the successful implementation of hydroelectricity generation in rivers holds great promise for the feasibility of our similar proposal. What distinguishes *Fl'eau*, however, is that instead of producing electricity for the electric grid more generally, we are suggesting the direct integration of this electricity in the public transportation network.

As is evidenced by the current work around New York City's Roosevelt Island, the momentum of the engineering innovation in the nineteenth and twentieth centuries has enabled the implementation of sophisticated energy generating networks in the twenty-first century.

Today, hydroelectric system reside in rivers, oceans, and dams across the globe, generating electricity on the order of several megawatts (10^6 watts). The most successful hydroelectric generators in rivers reside in Ontario, Canada,[22] but, as of yet, no nation has directly linked these generators to their public transportation networks.

It was brought to our attention by Michael Molitor, a local expert in sustainability policies and initiatives, that in 2010, the government in Paris proposed the installation of eight hydroelectric turbines in the Seine at four locations.[23] Clearly, this project did not come to fruition. In examining the reports on this attempted project, we came to the conclusion that it failed for two reasons.

While the proposal outlined a specific plan for installing the turbines, the use of the produced electricity was not specified. We believe that the pointedly focused use of hydroelectricity in our proposal sets our present attempt apart from the past. More significantly, perhaps, is the present political landscape. In 2010, the Mayor of Paris was Bertrand Delanoë, and much of his policy was concerned with improving quality of life for Parisians. (Most notable, perhaps, is his creation of the Paris Plage, transforming the Seine's banks into a beach in the summer). Current Mayor Anne Hidalgo is much more environmentally focused. Her implementation of Car Free Day and her proposed ban of diesel cars illustrate her dedication to sustainability in Paris, and it is precisely this political shift that makes us confident in our proposal's ability to have success where other's have faltered.

Mayor Anne Hidalgo

“Hydroelectric power seems as natural as, well, water.”

The New York Times

Introducing a sustainable source of self-generating energy carries the potential to reduce city expenditures on produced electricity for the RATP system. Even nuclear energy, while sustainable, requires an input of funds to continue producing electricity. Our proposal uses the constant flow of water in the Seine to provide hydroelectricity with little to no funding after the initial installation. This potential for expenditure reduction makes our proposal quite fiscally attractive.

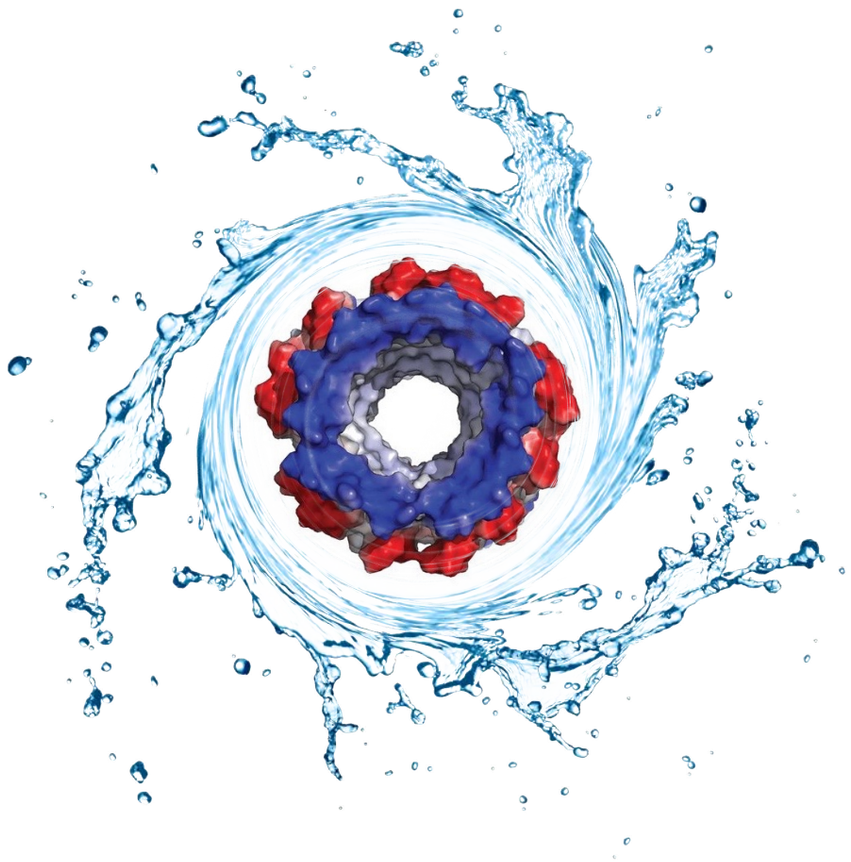
As electricity is exorbitantly expensive to store, it is practical to use it as quickly as possible. Our approach to hydroelectric power not only eliminates the need for long term electricity storage, but enables the direct integration of the generated electricity into the transportation backbone of Paris. Our proposal, therefore, is an innovative utilization of a technology that has consistently proven to be reliable and successful. Just as Fourneyron sparked a pathway of innovation that has led to gigawatts of hydroelectrically generated electricity, so too can Paris set a modern example of the possibilities associated with urban-conscious hydroelectric engineering.

A Logistical Perspective

It is helpful to analyze the ATP synthase mechanism more closely in order to more poignantly illustrate the inspiration for our implementation design. While the chemiosmotic potential of the proton gradient has been previously established, we have not yet discussed the mechanism by which this gradient powers the turning of the synthase's turbine.

This occurs through a channel attached to the F_0 component, such that the flow of protons is highly focused.[24]

Returning to our discussion of fluid mechanics, we can employ the principles of mass continuity and conservation of momentum to explain the mechanical benefits of such a channel. As mass cannot be created or destroyed, focusing a given mass of water in a small area will increase the pressure of that fluid flow, given a constant velocity vector.[25] As the Seine flows in a laminar fashion, the velocity of its flow may be considered constant, thereby enabling the continuation of this analogy.



ATP Synthase Proton Channel, seen from above, surrounded by flowing water
Edited by Harvard Summer School

An obvious choice to mimic this proton channeling would be to dam the Seine at strategic points to increase fluid pressure. As previously mentioned, this is likely to be aesthetically displeasing and highly expensive.

Fortunately, the Seine already has the infrastructure for these channels. The frequent bridges that traverse the river provide firmly defined channels in which our turbines may be installed. Given the relatively shallow depth of the Seine (9.4 meters on average) and the presence of concrete pillars that create divisions in the river, placing the turbines under the bridges in the Seine would provide the optimum power output for the Seine's input flow rate of approximately 500 cubic meters per second.[26] Ideally, the turbines would be installed in locations that have both bridges to optimize flow as well as proximity to the relevant RATP lines. Fortunately, these factors coincide in many cases.


Rigid structure of Pont Neuf

In the instance of the Métro 4, *Fl'eau* has the potential to generate 18 - 24% of the subway's electricity requirements. (See mathematical and physical calculations on the following page).

$$\text{Hydropower} = \text{Efficiency x Pressure Drop x Flow Rate}$$

$$H = \eta \times (\rho \times g \times h) \times Q \tag{1}$$

$$H = 0.30 \times (1000 \times 9.8 \times 0.025) \times 500 \tag{2}$$

$$H = 36,750W \tag{3}$$

$$H = 36.75kW \tag{4}$$

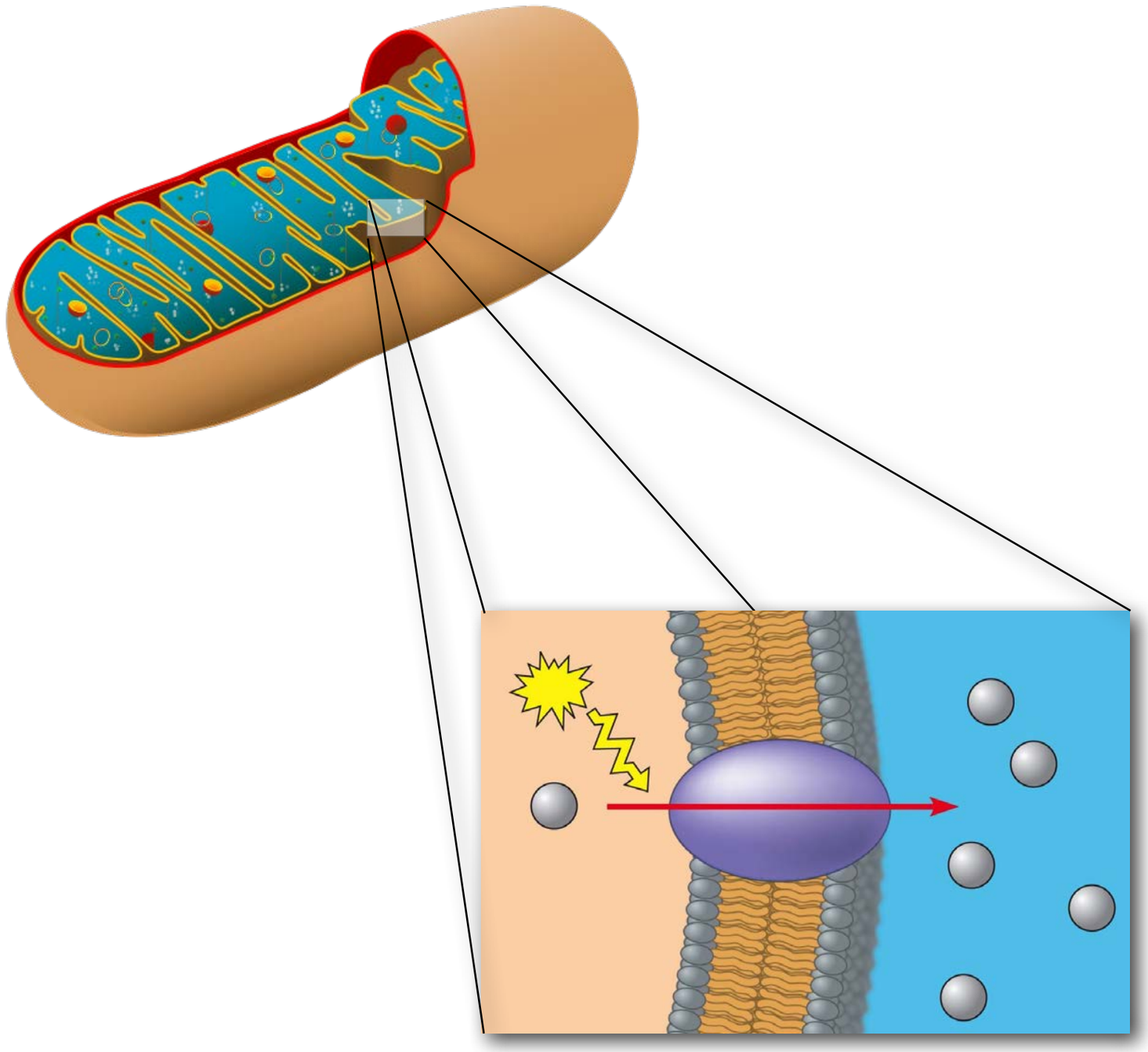
$$13\ \frac{kWh}{km} \times 12.1\ km = 157.3\ kWh \tag{5}$$

$$\frac{36.75}{157.3} = 0.234 \tag{6}$$

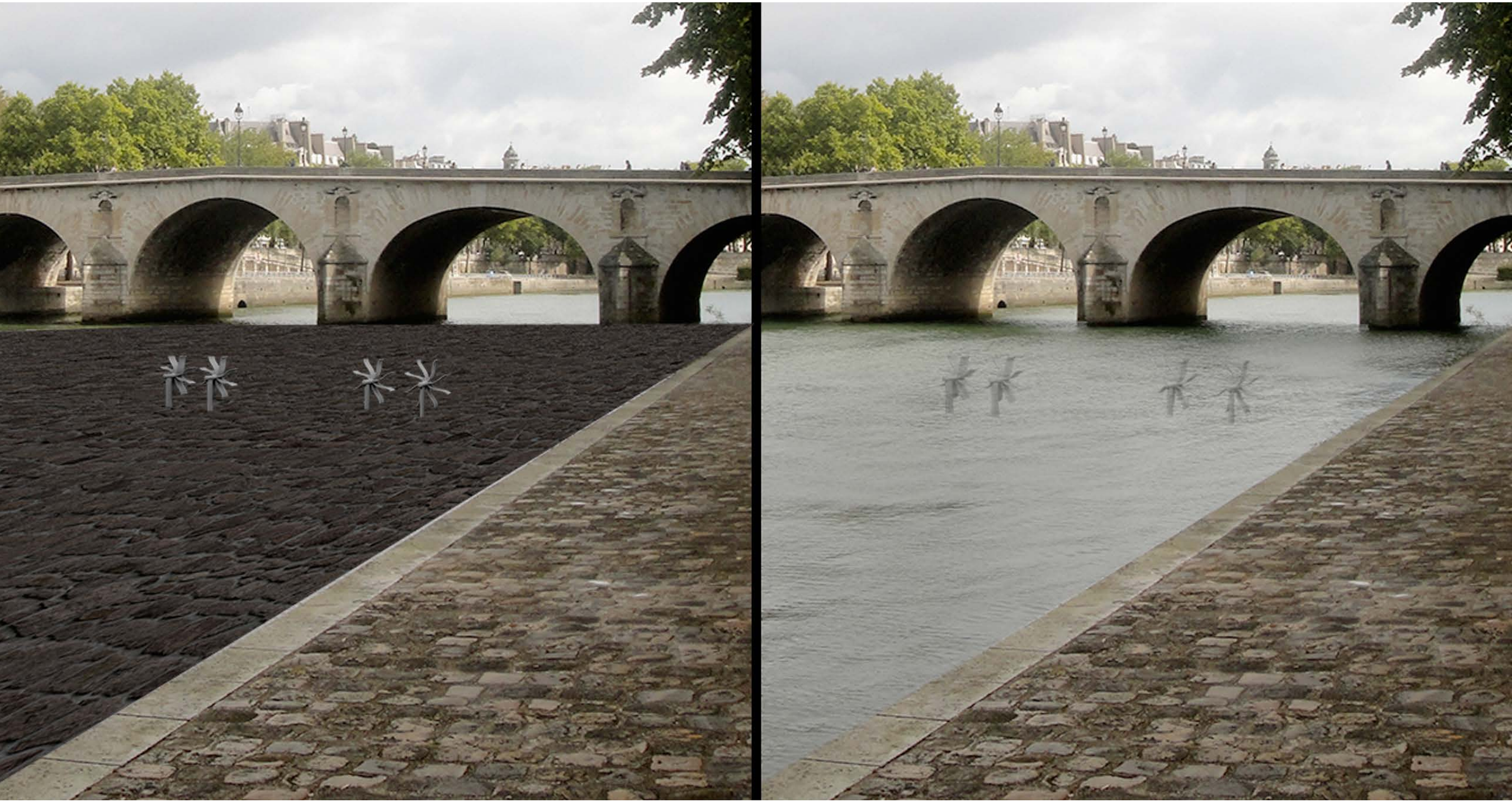
Equation (1) expresses the mathematical relationship between the physical properties of the river, the mechanical properties of the turbine, and the potential for hydropower. The values in Equation (2) represent the following: We estimate a 30% efficient turbine.

The density of water, ρ, is 1000 kg/m^3, the acceleration due to gravity is 9.8 m/s^2, and the height, h, was calculated using the potential for gravity to affect the flow of water across the height of the blades of the turbine. The value of Q is the flow rate of the Seine, 500 m^3/s, as previously mentioned. This yields a hydropower potential of 36.75 kW, as seen in Equation (4). Taking the electricity requirements of the Métro 4 as an example, 13 kWh/km, and multiplying it by the length of the Métro 4 track, 12.1 km, we see a power requirement of 157.3 kWh, shown in Equation (5). Equation (6) takes the results of Equations (4) and (5), illustrating the capacity of our turbine system to produce approximately 23% of the electricity necessary to power the Métro 4. We took this line as an example because it ideally intersects the Seine under the Pont Saint-Michel.

This optimization is inspired by the ingenuity of the ATP synthase. By locating itself across the inner mitochondrial membrane, for example, the proton gradient may be created in the inter membrane space. This smaller volume makes the task of creating a strong chemical gradient much simpler, and generating ATP from ADP within the enzyme itself allows for the most efficient use of mechanical energy, as a minimal amount is dissipated in transport or storage. These principles guide our design plan, as focusing the flow of the river will maximize the electricity generated by the turbines, and the proximity to the subway lines will idealize its utilization.



Magnified view of inner mitochondrial membrane
Edited by Harvard Summer School



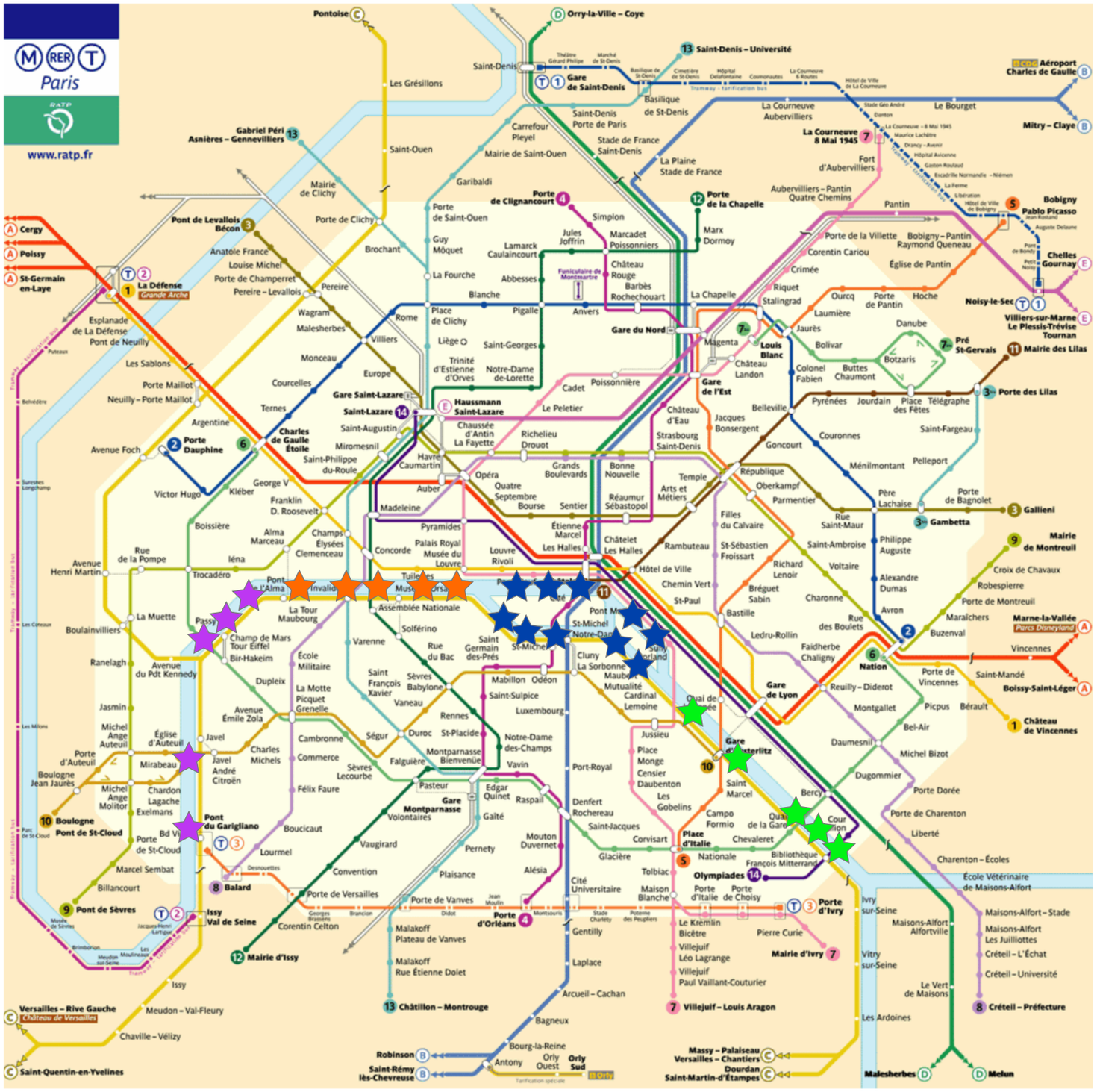
Visualization of turbines in the Seine
Created by Harvard Summer School

Phase 1 Installation

Phase 2 Installation

Phase 3 Installation

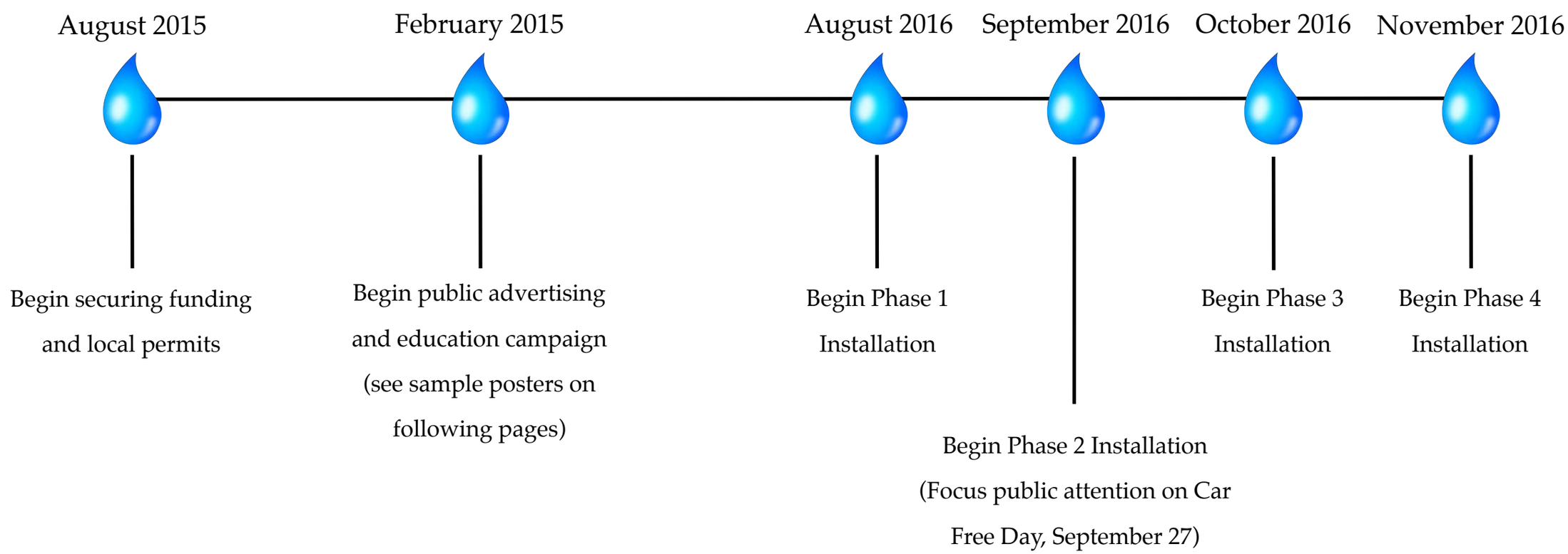
Phase 4 Installation



Map depicted proposed phases of installation

Created by Harvard Summer School

TIMELINE



Similar hydroelectric initiatives are scheduled to take between 2 and 5 years to reach completion, depending heavily on the scope.[27] Given the depth of the Seine, we foresee a 15 month timetable from project approval to completion. The predicted duration of this project is a result of the coordination that will be required between the city and the RATP to negotiate potential line closures as well as possible ferry tour interruption.

Ideally, construction would take place at night or on holidays when the RATP network is already closed. The minor inconveniences posed by this project's construction, however, are far outweighed by the future implications.

Proposed public advertisement
Created by Harvard Summer School

"Today the city seems like a perfect argument for the value of preserving the past, but with a bit more historical perspective, Paris also makes a case for the virtues of allowing enormous change."

Edward Glaeser, ***Triumph of the City***

Even in the shorter term, this proposal has the potential to create dozens of new career positions and augment the available positions of existing jobs. These opportunities will be varied in skill, labor, and education requirements, providing avenues for work for a wide array of citizens. Again taking other successful hydroelectric projects as examples, we predict a budget requirement of approximately 1.8 million euros (see next page). This initial investment, while large, will have substantial returns, both monetary and otherwise, in the years to come.

Investing now in hydroelectric power in the Seine will result in saving the funds that are currently used to power the RATP network. By harnessing the mechanical power in the Seine, ultimately powered by the English Channel, a previously untapped, limitless source of green energy is possible. The implications of this proposal are not limited to Paris today. Rather, the benefits extend to the world of tomorrow.

BUDGET

ITEM	DESCRIPTION	PREDICTED COST
Hydroelectric Kinetic Turbines	These machines will be purchased for installation at our proposed 26 sites.28 Cost calculation: 2737.60 € per turbine x 104 turbines = 284,710.40 €	284,710.40 €
Turbine Installation and Electrical Integration	There is a cost for rewiring the electrical system of the métro to incorporate the new source of power. This is based on approximated cost per kilowatt-hour.29 Cost calculation: 10,610 € per kWh x 36.75 kWh = 389,917.50 €	389,917.50 €
Labor	This is approximated using the national monthly minimum wage for France, the projected 4 month construction period, and the number of workers. Cost calculation: 5830.08 € x 4 months x 40 workers = 932,812.80 €	932,812.80 €
Advertisement and Education	This estimates cost of interactive touch screen displays, application development, and printing cost for posters.	200,000 €
TOTAL		**1,807,440.70 €**

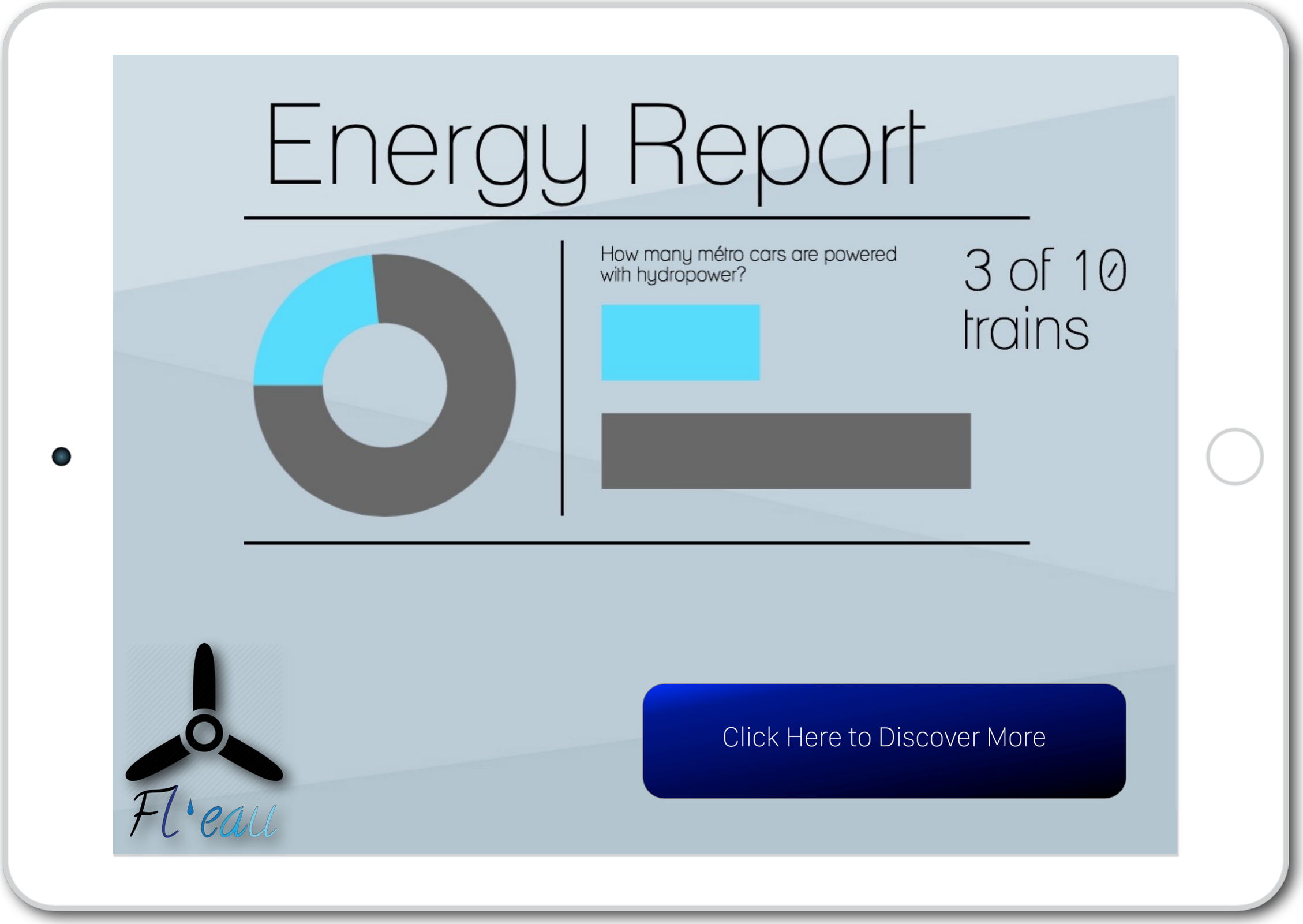
Checking In

Assessing the success of this proposal would be relatively straightforward. From a purely statistical perspective, the amount of electricity saved by installing these turbines could be measured by monitoring the wattage used from various sources of electricity (i.e., nuclear, coal, hydroelectric) over time and comparing the relative portions contributed by each generation technique. Alternatively, the assessment could be conducted from a fiscal perspective, analyzing the money saved by the city in the public transportation department.

Illustration of Nuclear, Coal, and Hydroelectric power, represented graphically
Created by Harvard Summer School

Public works, however, are not only concerned with the proverbial bottom line. In order to ensure sensitivity towards the populace, a citizen-centric perspective must be addressed as well. By coordinating with the RATP, the Mairie de Paris could discern which lines experience the least amount of traffic across the Seine so as to prioritize the order in which line closures occur. This would be primarily based on minimizing impact while maximizing return, perhaps leaving the busiest metro and RER lines for last, thereby promoting a higher level of experience and expertise on the part of the construction workers and designers. In the interest of maintaining citizen morale, a small marketing team could design and display advertisements (see following page) in the metro stations, both warning of line closures far in advance and illustrating the future benefit of the project. Additionally, surveys could be conducted throughout the proceedings of the project to gauge citizen response and mitigate any displeasure in its early stages.

Conceptualization of potential closure poster.
Created by Harvard Summer School



Proposed interaction education panel/application
Created by Harvard Summer School

The fiscal and statistical analyses, therefore, would be conducted primarily following the completion of the project while the humanistic assessments would occur throughout. While this proposal is significantly focused on the installation of a hard infrastructure, the attention paid to the human element and societal impact will give this project value in the eyes of the citizens. By involving the citizens, the vitality of the city is strengthened. This proposal seeks to reimagine the infrastructure of today so as to empower the citizen of tomorrow, evolving the Smart City in the process.

Water. Métro. Citizen impact.
Created by Harvard Summer School

LOGIC PLAN

Objective	Reason	Method
Parisian Response	Ensure that minimal inconvenience is caused to commuters during construction period.	Survey RATP customers quantitatively to gauge the impact on their daily commute (Heavy, Moderate, Small, None).
Fiscal Return	Analyze expenditure reduction as a result of turbine installation.	Compare city expenditures in euros on subway electricity before and after installation.
Electrical Return	Quantify energetic effectiveness of installing the turbines.	Compare electrical demand in kilowatt-hours of subway network from nuclear and coal sources before and after installation.
Collective Awareness	Increase public knowledge of sustainable energy and the impact of hydropower in the Seine.	E-mail an online survey before and after the installation of educational panels to compare relative levels of citizen knowledge of sustainable energy.

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ATP Synthase Space-Filling Structure: <http://www.ks.uiuc.edu/Research/f0atpase/structure.jpg>

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ATP Synthase Cartoon Diagram: <http://www.bio.miami.edu/tom/courses/protected/MCB6/ch12/12-24.jpg> Edited by Karolina Ladino Puerto

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