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27th CIRP Life Cycle Engineering (LCE) Conference

# Towards sustainable business model and sustainable design of a hydro generator system dedicated to isolated communities

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## Abstract

Rural electrification is a complete transformation with even greater impacts in remote areas. Designing appropriate technologies that meet the tough requirements of isolated communities remains a challenge. Through the use of hydrokinetic energy, we take some isolated villages in French Guiana as examples to propose an electrical service keeping in mind that energy access is not an end-in-itself, the real goal being the sustainable development of the community. The triple layered business model canvas and a multi-criteria assessment method help to imagine the value proposition and the design of the solution in a sustainable approach.

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**Keywords:** Low-tech; sustainable design; sustainable business model; triple layered business model canvas; multi-criteria assessment method; renewable energy; hydro generator; energy access; isolated places.

## 1. Introduction

Energy and development are connected. Besides, energy is linked to quality of life, hence quantity, quality and distribution of energy are strongly related to the human development index in a country [1]. Up to a certain level, the available amount of energy per habitant in a country is roughly proportional to its state of development. Mostly based on fossil fuels and less on renewable primary sources, the energy consumption keeps thus increasing in developing countries in order to assure their multi-faceted development.

As universal energy access is one of the main objectives of sustainable development [2], international agencies such as the International Energy Agency or the United Nations regularly publish reports on the achievement of the 7th Sustainable Development Goal: “Ensure access to affordable, reliable, sustainable and modern energy”. In 2017, nearly 840 million people worldwide still had no access to electricity compared to 1.2 billion in 2010, representing an average electrification rate of 89 % (83 % in 2010) [3]. Behind a global increase in

electrification rates, a diversity of situations and trends is hidden and a worldwide access to electricity is far from being achieved. In developing countries, the priority remains capital cities and main regions, leaving numerous isolated places without a connection to the main grid (urban electrification rate 97 % versus 79 % for rural rate) [3].

Among those regions, communities living near rivers or seashores are likely to rely on local energetic resources: they may use river or ocean energies which are abundant and available in several forms. On the one hand, small, micro and even pico hydroelectricity using potential energy is well established, for example in Asia [4] but on the other hand existing kinetic energy technologies target more industrialized countries’ needs than those of isolated places [5]. A demand for specific solutions based on river or tidal energy and suited to isolated regions is still to be developed.

In this paper, the proposed energy access solution is based on a hydro generator system for in stream river generation. This meets the requirements of an isolated community living near a river with an interesting hydrokinetic potential. The

adopted approach is dedicated to target the most sustainable solution for developing countries or off grid places, both need devices to produce clean energy to enable their growth. We use two different and complementary tools to design our solution: the triple layered business model canvas as TLBMC recently proposed by A. Joyce and R.L. Paquin in 2016 [6] and our multi-criteria assessment method used as a decision-support tool presented in 2018 [7]. In fact, the assessment of a product can be approached from two complementary standpoints: either as a value proposition in relation to the identified need of a user, or as a technical solution for which the design and associated processes must be conceived. The first angle is addressed with TLBMC tool and the second one with our multi-criteria assessment method. Taking various criteria into account (technical, economic, environmental and social) as well as the whole life cycle of the product, these processes come under the domain of life cycle engineering [8] and help technology developers, project coordinators and decision-makers in targeting the optimal energy solution.

The process is theoretically illustrated on a case study to develop a hydro solution for an isolated community living near a river in the Amazonia forest in French Guiana.

## **2. First energy access of isolated places: hard constraints but some possibilities**

Access to energy means a demand for energy in the form of electricity and supply solutions combining technical equipment and associated economic models. However, developing peoples seeking to increase their quality of life are behind the terminology ‘access to energy’. Electricity is a driver of human progress and electrification techniques should be thought of with a sustainable development perspective in mind.

### *2.1. From the demand side, energy for development*

Before the electrification of isolated regions, the energy consumption may be limited to transport, cooking with coal or wood and lighting with oil lamps [3]. In this context, daily life is difficult, so as earning money with primary activities. For an electrification project, the demand will be defined by the future electrical uses: from the most basic to the most demanding, there is a wide range of possibilities.

When it comes to electrification rates, the binary vision of the situation masks the real granularity of access to energy. To overcome this misjudgment on the measurement of energy access, ESMAP and the World Bank built a multi-tier energy access framework in 2015 [9]. The method enables a better understanding of the impacts of energy on socio-economic development by shifting to the consumer's side and leaving production technologies aside. The study covers energy for households (electricity, cooking, heating), productive or professional engagements and community facilities. There are five levels of access to energy, rated from 0 to 5, where level 0 equals zero access and level 5 equals comparable access to industrialized countries. The access is incremental, evolutive and allows more and more services as the installation grows.

The 1st level allows spot electric lighting and mobile charging, the 2nd level adds general lighting, television and fan, the 3rd, 4th and 5th levels add more and more powerful household appliances and for longer periods of time. To climb the first ladder the soon-to-be electrified community will need a small amount of power and energy.

### *2.2. From the supply side, existing possibilities*

In developing countries, the electrification of dense urban areas by a conventional electricity grid is a high priority compared to the supply of less dense rural areas, even though the vast majority of the population is rural [10]. The first solution for rural electrification today is to connect the isolated place by extending the existing electricity grid. Widely used in Africa, it can raise issues of distance-related costs and planning of network infrastructure and operation. Instead, the current strategy is to expand the network only in densely populated and economically viable areas, install mini-grids in remote villages and propose individual systems in sparsely populated areas with low potential demand.

Isolated places having individual system or mini-grid present spatially close production and consumption systems which is an asset regarding energy transportation. Moreover, production always fits consumption i.e. production plants can be updated following the local development and energy demand growth thus providing adaptability.

In 2016, 133 million people had at least access to the 1st level of energy through individual systems or mini-grids, including 53 million in Africa and 76 million in Asia [11]. On all off-grid solutions, solar technology represents about 85% of the equipment [3]. Mini grids are an intermediate solution between the conventional grid and individual systems over the power range 1 kW-10 MW [12]; more than 9 million people are connected through mini-grids in 2016 [11]. Used technologies are diesel generators or renewable energies with hydropower in the forefront, followed by solar and biomass [12]. Individual solutions offer primary services such as lighting and phone charging, which are 1st and 2nd tiers of the access ladder. Almost all individual systems are based on photovoltaic solar energy: 100 million people use solar lamps (< 11 W) offering 1st level services, 24 million solar home systems (SHS) offering 2nd level services [11].

These technologies have pros and cons regarding technical, economic, environmental and social fields. Gensets are quite affordable among others, easy to use, robust, reliable and they produce electricity steadily. However, they need fuel whose price usually increases and they are not environmentally or health friendly. Hydropower has strong advantages but is very site-specific. Solar PV is more sophisticated than gensets and still more expensive to buy but some villages may be subsidized by banks, governments or NGOs.

Finally, rural electrification cannot be limited to the technological issue alone; it is much wider and more complex because it affects the economic, financial, political and social spheres. Today, electricity distribution models and associated business and financial models are a barrier in many projects [13]. The major difficulty is due to scarce financial resources

of isolated populations and low profitability of activities (agriculture, livestock, small-scale fishing). Mechanisms and tools nevertheless make it possible to overcome financial difficulties with micro-payments or micro-credits (PAYGo, mobile banking).

### *2.3. Alternative systems for isolated places with hydrokinetic resource*

Many isolated communities are located near water points such as sea or river. Those near a river with high hydrokinetic potential could use energy from the current to produce electricity. Among the existing devices, the majority is developed by and for industrialized countries [5]. Such devices are complex, hard to repair or irreparable by the community; they can be qualified of high-technologies and they meet the strict specifications of isolated places with difficulty. Developing countries need specific clean energy technologies based on their renewable resources, as well as their financial, material and human ones.

An alternative to these high-tech renewable energies would be using simple, robust, even proven and long-established technologies: this is low-technology [14]. First requirements of these redesigned technologies are their low cost, high reliability and/or ease of maintenance in order to produce as much time as possible. These systems may not be as effective in the energy extraction and conversion processes but they may better address developing countries concerns. For microgrids maintained by the community, power supply systems should be adapted to the population and its means to ensure sustainability. New constraints on the design of renewable energies are emerging by placing human beings and their environment at the centre of the problem (as users, maintainers and producers). Thus, grid planning should broaden its vision with new fields of constraints and find unconventional solutions. From the design phase onwards, energy projects must be assessed globally according to technical, environmental, economic and social criteria in order to find the most sustainable solution for the community.

### **3. Imagine a sustainable solution for isolated regions**

When dealing with an innovative solution, the process counts five steps: context understanding, need analysis leading to problem formulation, specifications definition of imagined solutions, sketching or pre-dimensioning of the solution, sizing and implementation of the solution [15]. This section focuses on the decisive phase of solution design with specifications definition and sketching.

The sustainable energy access solution can be imagined from two angles using the corresponding tools: from the customer's point of view (exterior) and from the designer's point of view (interior). The exterior vision i.e. the value proposition is built using the triple layered business model canvas as TLBMC [6]. This tool promotes business model innovation taking sustainability into account. It upgrades the original business model canvas with an environmental canvas based on a lifecycle perspective and a social canvas based on

stakeholder perspective. TLBMC structures sustainability issues and multiple types of value (economic, environmental, social) in business model. The interior vision i.e. the technical specifications of the system is built using our sustainable design tool. In a previous article, we introduced a multi-criteria assessment method which can be used as a decision-support tool for the different stakeholders to target the sustainability of an electrification project [7]. Our tool broadens designer's vision at the sketching phase with technical, economic, environmental and social criteria. Both tools belong to life cycle engineering and take various criteria into account as well as product life cycle to target the most sustainable solution at the planning stage [8]. Used together in our topic, they complement each other in the imagination of exterior and interior views of the hydro generator system.

Above all, we would like to anchor our challenge on a real background to give it more authenticity. French Guiana region is chosen as a study case.

#### *3.1. French Guiana study case*

French Guiana is an overseas department and region of France located in South America between Suriname and Brazil. More than 98 % of the land is covered by primary rainforest [16]. The total population is close to 300,000 inhabitants. The densely populated coast with the main cities can be distinguished from the municipalities of the interior where 10 % of the population live dispersed on the rest of the land. Municipalities in the interior are extremely isolated; they can only be reached by river or air.

The coast has a conventional electricity grid with production, transportation and distribution systems whereas only some of the isolated municipalities have their own grid with a maximum production of 2 MW [17]. Energy mix is based on hydroelectricity (64 % of production in 2014) and fossil-fired power plants [16]. Recently the region saw the installation of biomass units and solar PV.

Municipalities in the interior have a lower access rate with less than 50 %. Also, thermal power plants produce electricity at a high cost reaching 1,300 €/MWh that is 5 times the average cost in the region and 10 times the sale price because fuel is delivered by pirogue [16]. Hence, the development of renewable energies in the municipalities of the interior is not only of environmental interest but also of economic interest. There are currently roughly 200 identified isolated communities with 1 to 20 households waiting to be electrified.

Rivers provide already a lot of energy to the territory thanks to few dams but in-stream river power plant could be more adapted with less environmental impacts. There were few studies or experiences using hydrokinetic energy. In 2013, HydroQuest installed a hydro generator system to supply Camopi village on Oyapock river, 200 inhabitants powered by a diesel generator. In 2017, the PhD of Boutouchent delivered a hydrodynamic modeling of Maroni river to find suitable sites for hydro turbines [18].

Using both tools, the next sections discuss the sustainable specifications of an electrical system powered by a hydro turbine for remote communities of French Guiana.

### 3.2. Business model of our hydro energy solution

In this section, we use the first layer of the TLBMC to define the most sustainable business model of the electrical system [6], [19]. Fig 1 shows the Business Model Canvas of our solution.

The value proposition is the electrical service with production and distribution systems sized to reach first tiers of energy access. The village is the customer with its households, small businesses and public places. As project developers, we need to identify the activities, resources and partners of the electrical service. We choose to think local and to put the community as a strong stakeholder included in the installation, the management and maintenance of the service after a training. Our choices are made to target a win-win situation between all stakeholders. Because the community has low financial capabilities: costs are reduced and revenues increased. Costs are investments for the hydro turbine and the distribution system, and operating costs. Our solution should be cheaper than a diesel generator where costs are driven by fuel price and its expensive transportation. The low-tech approach is an advantage for both investment and operating costs. Revenues take subsidies into account even if it is recommended to do without them. Finally, the electricity tariff should be less than or equal to the household's energy bills before electrification.

### 3.3. Environmental model of our hydro energy solution

This part and the next one add the sustainable approach to the traditional business model [6]. The environmental table is inspired by life cycle analysis of the system and invites to generate more environmental benefits than impacts. Fig 2 shows the environmental layer of the TLBMC applied to our solution.

The chosen functional value is the ability to provide electricity to the community over 20 years considering that the system's sizing would be outdated after that period. Again, we choose a local approach for production, materials, supplies and out-sourcing. The use phase sees clean energy production then a clean energy consumption that is a benefit compared to other technologies like diesel generator or oil lamps. End-of-life of the components is (in this order): reuse, repair and recycle. Environmental impacts can be evaluated with a life cycle assessment and compared with other solutions. Existing LCA on microgrids and off-grid solutions show that electricity systems using a diesel generator have more impacts than PV system [20], [21]. At the end of the design phase, the bill of material will allow the LCA of the hydro turbine. Finally, impacts on the river should be reduced as much as possible.

Partners	Activities	Value proposition	Customer relationship	Customer segments
Resources	Channels			
<ul style="list-style-type: none"><li>Financial : development and national banks</li><li>Political : local decision-makers and government</li><li>Industrial: national or regional manufacturers</li><li>Business : local spare parts suppliers and electrical equipment suppliers</li></ul>	<ul style="list-style-type: none"><li>Installation and maintenance of the system</li><li>Retrieval of subscriptions and payments for the service</li></ul> <ul style="list-style-type: none"><li>Location : river potential and conditions to install a hydro generator</li><li>Production and distribution systems in working order</li><li>Local population at all levels</li><li>Intellectual: design, development, management of the service and system</li><li>Technical: installation, maintenance</li><li>Financial: commercial, accountant</li></ul>	<ul style="list-style-type: none"><li>Electrical service to reach the first energy tiers. lighting, phone charging, ventilation, small electrical appliances</li><li>Production system with a hydro generator which is sustainable and financially and materially accessible</li><li>Distribution system with wires and meters</li></ul>	<ul style="list-style-type: none"><li>Satisfaction</li><li>Confidence</li><li>Accessibility</li></ul> <ul style="list-style-type: none"><li>Project initiation through stakeholders</li><li>Electrical service at home</li></ul>	<ul style="list-style-type: none"><li>Isolated villages not connected to the electricity grid: households, small businesses, public places like health centers, schools and street lighting)</li></ul>
Costs		Revenues		
<ul style="list-style-type: none"><li>Investment costs of the electricity production and distribution system</li><li>Operating costs: maintenance, no fuel (significantly reduced OPEX compared to diesel generator)</li><li>Reduced costs through local approach and system simplification</li></ul>		<ul style="list-style-type: none"><li>Project subsidies from financial partners</li><li>Reinvested income in the system</li><li>Customer subscriptions: monthly fee. Electricity tariff in accordance with users' payment capacities with microcredit facilities</li></ul>		

Fig. 1. Business Model Canvas for the hydro energy solution.

<b>Supplies and out-sourcing</b> <ul style="list-style-type: none"><li>• Manufacture of all production and distribution system components and tools for installation and maintenance</li><li>• Energy and water for processes</li><li>• (Electrical equipment: light bulb, various appliances)</li></ul>	<b>Production</b> <ul style="list-style-type: none"><li>• Local manufacture of spare parts and some tools</li></ul>	<b>Functional value</b> <ul style="list-style-type: none"><li>• Provide electricity to the community over 20 years</li></ul>	<b>End-of-life</b> <ul style="list-style-type: none"><li>• Prefer repair for the system and its components</li><li>• Reuse components for other local systems</li><li>• Recycle if not repaired or reused</li></ul>	<b>Use phase</b> <ul style="list-style-type: none"><li>• Clean energy produced by the hydro generator (no emissions during production)</li><li>• Clean energy distributed and used for lighting and other uses</li></ul>
	<b>Materials</b> <ul style="list-style-type: none"><li>• As local as possible (wood, steel, transformed plastic waste), possibly resulting from recycling: spare parts and some tools</li><li>• Energy and water for processes</li></ul>		<b>Distribution</b> <ul style="list-style-type: none"><li>• Local transportation to carry components, tools and spare parts: road, river</li></ul>	
<b>Environmental impacts</b> <ul style="list-style-type: none"><li>• Impacts of the production and distribution system with a complete LCA</li><li>• Local impacts on the river during installation and use phases</li><li>• No emissions during the use phase except for maintenance</li></ul>		<b>Environmental benefits</b> <ul style="list-style-type: none"><li>• Electricity production with renewable energy compared to a diesel generator (reduced greenhouse gas and pollutant emissions)</li><li>• Local processes and materials to reduce environmental impacts</li></ul>		

Fig. 2. Environmental layer of the TLBMC for the hydro energy solution.

### 3.4. Social model of our hydro energy solution

The third layer of the TLBMC is based on relationships between stakeholders and towards the service [6]. In essence, an electrical service is a social benefit for the community. It is however possible to foster sustainability in maximizing positive impacts on all stakeholders involved in the project. Fig 3 shows the social layer of the TLBMC applied to our solution.

The social value is community development (better quality of life, health, wealth, education...) thanks to the energy access and community involvement in the project. The community and the local decision-makers should be consulted all along the project's life. Local households and businesses benefit the most from the changes but effects can be seen in the extended community and even at a regional scale if the local approach is well-developed in the project. Service staff should come from the community and be trained for technical and economic activities. Social benefits like quality of life or working conditions need to be maximized compared to social impacts like electrical risks or increased working time. Finally, the hydro turbine must be compatible with the previous uses of the river.

### 3.5. Towards technical specifications of our hydro energy solution

This section focuses on the interior vision of our hydro energy solution. As system designer we use our sustainable design tool to sketch the system [7]. The outline of our multi-criteria assessment method is summarized in Table 1. Nearly all the variables in Table 1 were already included in each layer of the TLBMC for our solution but here the variables are studied to provide design criteria. At the planning stage, the designer needs to understand and have in his mind all the

sustainability issues of the electrification project. On a particular project, our decision-support tool encourages discussion on the relative importance of the criteria and allows the opinions of all stakeholders to be considered upstream, which is a guarantee of success and sustainability [22].

Thanks to his expertise, the designer can transform the most important criteria of sustainability in design features on the subsystems of the electrical installation (hydro turbine, distribution system) and then on the components themselves (turbine, generator...). At the end of this procedure, previous criteria are translated into a complete list of technical specifications split in technical performance (power, energy, efficiency, availability, power factor) and appropriate design (size, complexity, reliability, eco-design).. From the observation of the severe constraints associated with isolated places, we choose low-tech attributes like simple, reliable, robust, maintainable, different from the habitual 'most-efficient-at-the-lowest-price' motto [14]. Those systems do not only provide an electricity supply, they give as well energy self-sufficiency and resilience that is important to fulfill sustainability expectations. Furthermore, the local approach for supplies, out-sourcing and materials put strong constraints on the design as well as the fact that the village should be trained on the system.

For the production, we think the hydro turbine can be made of basic and robust or repairable components: wooden or steel blades, no speed multiplier, an original direct-drive asynchronous generator in an autonomous mode, no power converter. The distribution system can be reduced to wires without meter. Indeed, the first tier of energy access is very basic so that the electrical installation can be reduced to the minimum: useful but non-essential parts are removed [9]. If the community has more resources, it can directly invest in a more advanced microgrid with a power converter and even a storage system to access upper tiers.

<b>Local communities</b> <ul style="list-style-type: none"><li>• Development of the extended community through new economic and cultural activities enabled by energy access and the development of those who have energy</li><li>• More regional activities related to the production, installation and maintenance of the hydro solution</li></ul>	<b>Governance</b> <ul style="list-style-type: none"><li>• Population and local decision-makers involved from the beginning of the project, consulted for all decisions</li><li>• Project developers close to the field to understand stakeholders and build trust</li></ul> <b>Employees</b> <ul style="list-style-type: none"><li>• Local population engaged for the installation and maintenance of the system</li><li>• Technical training provided to the community</li><li>• Local employees responsible for the service and income collection, with good work and remuneration conditions</li></ul>	<b>Social value</b> <ul style="list-style-type: none"><li>• Global community development through sustainable energy access</li><li>• Community involvement in a collective project for the good of all</li><li>• Improvements in quality of life, well-being, health, education, safety, wealth, entertainment</li></ul>	<b>Societal culture</b> <ul style="list-style-type: none"><li>• Modified community life: new usages and lifestyles</li><li>• The service enables you to work longer and combine activities</li><li>• The household's personal electrical use can reduce community life</li></ul> <b>Scale of outreach</b> <ul style="list-style-type: none"><li>• Amplify the benefits of the system at the local level</li><li>• Locally: in households and businesses, in community centers</li><li>• More widely with regional and national implications</li><li>• Limit rural-urban migration</li></ul>	<b>End-user</b> <ul style="list-style-type: none"><li>• For households: increase in quality of life, wealth with income-generating activities, education and health</li><li>• For companies: increased technical means, improved working conditions, increased productivity with the possibility of extending working hours</li></ul>
<b>Social impacts</b> <ul style="list-style-type: none"><li>• Compatibility with the river's uses (agriculture, fishing, tourism, leisure)</li><li>• Increased working time</li><li>• Electrical risks: employee and public safety</li><li>• May lead to electricity dependence</li><li>• Different roles in the community (jealousy of service employees)</li></ul>			<b>Social benefits</b> <ul style="list-style-type: none"><li>• Quality of life, health, education of children (less or no child labor)</li><li>• Advances in working conditions</li><li>• Community engagement through participation during the project, training and maintenance</li></ul>	

Fig. 3. Social layer of the TLBMC for the hydro energy solution.



Table 1. Multi-criteria assessment method [7].

Technical	Economic	Environmental	Social
Fabrication	Financial perspective	Global impact	Community development,
Installation	Job creation	Local impact	involvement
Operation	Economic environment		Capacity strengthening
Maintenance			Education
End of life	Household budget		Client relation
			Security, safety

#### 4. Discussion

For this research work, we were alternatively outside and inside the box, respectively adopting the exterior and the interior viewpoint on the solution. Using the two tools on our energy access problem, we talked about similar variables of sustainability and came across complementary results to entirely imagine a sustainable hydro energy solution.

In reality, the exterior and interior visions are thought by distinct actors. If they do not interact and discuss sufficiently, the value proposition can deviate from the technical design. Furthermore, both methods appear to be appropriate to address all aspects of sustainability in the sketching phase which puts the project on good tracks for the future steps. However, their high level of richness can lead to handling difficulties and many trade-offs may be necessary in order to deliver an intelligible and practical set of specifications.

On another note, our sustainable hydro energy solution seem difficult to build in practice because the local approach we have adopted requires a very high level of knowledge about the region. For example, to explore the local manufacturing and repair, an accurate vision of country's industrial capacities and sourcing, current and foreseeable skills of the population are required as well as financing capabilities of the municipality. If the information is wrong, the imagined solution could be far from the best sustainable one and even unfeasible. Consequently, a strong collaboration between the stakeholders, local institutions, companies is compelled to increase the level of knowledge about one another in order to get a true regional development. In French Guiana situation, industrial capacity is weak and it is difficult to know whether the government wants to develop this sector and how quickly. Knowing this, manufacturing will have to be relocated to neighboring countries such as Brazil which leads to an increase of environmental, economic and social negative impacts. The sustainability of our solution is then deteriorated. It would be very instructive to discuss our proposal of hydro energy solution with the stakeholders in Guyana: local decision-makers, municipalities of the interior, industrial companies to sort feasible solutions from the others. In the end, starting from an ambitious solution and slightly deteriorating the result will always be better than starting from a standard solution and implementing sustainable adjustments.

#### 5. Conclusion

The paper covers the design process towards sustainability of a hydro generator system dedicated to the energy access of isolated communities such as in French Guiana. Two complementary tools are applied for this phase: the TLBMC adds environmental and social value to the economic business model and our multi-criteria assessment method helps the designer to broaden his view, discuss with stakeholders and find technical specifications to sketch a sustainable solution.

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