Environ Sci Pollut Res
DOI 10.1007/s11356-017-8749-3

4TH INTERNATIONAL SYMPOSIUM ON ENVIRONMENTAL BIOTECHNOLOGY AND ENGINEERING-2014

Analysis of the environmental issues concerning the deployment of an OTEC power plant in Martinique

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Received: 20 July 2016 / Accepted: 2 March 2017

Abstract Ocean thermal energy conversion (OTEC) is a form of power generation, which exploits the temperature difference between warm surface seawater and cold deep seawater. Suitable conditions for OTEC occur in deep warm seas, especially the Caribbean, the Red Sea and parts of the Indo-Pacific Ocean. The continuous power provided by this renewable power source makes a useful contribution to a renewable energy mix because of the intermittence of the other major renewable power sources, i.e. solar or wind power. Industrial-scale OTEC power plants have simply not been built. However, recent innovations and greater political awareness of power transition to renewable energy sources have strengthened the support for such power plants and, after preliminary studies in the Reunion Island (Indian Ocean), the Martinique Island (West Indies) has been selected for the development of the first full-size OTEC power plant in the world, to be a showcase for testing and demonstration. An OTEC plant, even if the energy produced is cheap, calls for high initial capital investment. However, this technology is of interest mainly in tropical areas where funding is limited. The cost of innovations to create an operational OTEC plant has to be amortized, and this technology remains expensive. This paper will discuss the heuristic, technical and socio-economic limits and consequences of deploying an OTEC plant in Martinique to highlight respectively the impact of the OTEC plant on the environment the impact of the environment on the OTEC plant. After defining OTEC, we will describe the different constraints relating to the setting up of the first operational-scale plant worldwide. This includes the investigations performed (reporting declassified data), the political context and the local acceptance of the project. We will then provide an overview of the processes involved in the OTEC plant and discuss the feasibility of future OTEC installations. We will also list the extensive marine investigations required prior to installation and the dangers of setting up OTEC plants in inappropriate locations.

Keywords Renewable energy · Power · Coastal management · Hot seas · Tropical area · Bathyal layer

Responsible editor: Philippe Garrigues

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Abbreviations

CNRS	National Centre for Scientific Research
DCNS	Shipbuilding, systems and service directorate
IRD	French institute for the development
Ifremer	French institute for study and exploitation of the seas
OTEC	Ocean thermal energy conversion
CTM	Territorial collectivity of Martinique
HDI	Human Development Index

Introduction

For many decades, our population and standard of living have both increased, leading to a critical energy situation (Panwar et al. 2011). Residential and industrial needs continue to rise,

Published online: 18 May 2017

although fossil fuel is increasingly rare. Fossil fuel discovery and extraction are themselves becoming increasingly expensive, the direct cost, i.e. cost of discovery, extraction and refining (Brandt 2011), and indirect costs, i.e. short-term environmental consequences of extraction implying use of chemicals (Rio Carrillo and Frei 2009; Clark et al. 2012) and medium-term consequences, i.e. the resulting greenhouse gas effects (Howarth et al. 2011). The concomitant rarefaction of other non-renewable resources such as minerals worsens the situation because of the increased energy needed for refining depleted ore (Hammond et al. 2013). Moreover, dependence on fossil fuels creates critical strategic vulnerability for non-producing states.

In this general context, renewable power to cater for increasing needs is a highly attractive yet challenging issue. Several techniques have been developed based on renewable power plants or devices disseminated on a domestic scale. Domestic installations use solar, geothermal, heat engine and wind energy technologies. Renewable power plants use the same energy sources in addition to hydroelectric, biomass and marine energy. The status of nuclear power plants remains controversial. Large installations favour efficient waste management, which is sometimes critical for disseminated devices, in particular, domestic photovoltaic installations. The overall goal is to be able to compete directly with conventional fuel-fired electric power stations, which generate 21.6% of the global greenhouse gas emissions (Havens et al. 2010). However, their size, the associated hazards or their location could limit the population's acceptance, especially if it is in close proximity to housing, and which could lead to objections to the creation of renewable energy power plants. However, in reality, renewable power plants are not massively replacing fossil fuel installations whatever the techniques involved. The renewable power plant's yield is often favourably paired with that of fossil fuels, but, with the exception of ocean thermal energy conversion (OTEC), most forms of renewable power production are intermittent. OTEC renewable power production is driven by the forces of nature, not by human needs as is, to a certain extent, the case of all modes of renewable power production.

In order to secure power production, managers try to mix power supplies, thus ensuring a constant power base load. In this context, the OTEC plant is an original power supplier, the first of its kind, exploiting the difference of temperature between warm surface water and cold deep water, thus providing continuous power. Used in an energy mix, OTEC aims to provide a constant power supply. OTEC technology, although developed decades ago, is now seeing progressive improvement such as power production efficiency which reduces the thermal difference needed for the process to be operational (Faizal and Ahmed 2013), especially because thermal techniques interact with geothermal solutions. Nihous (2005 and 2007) estimated the global resource available for OTEC at around 3×10^9 kW with the Atlantic representing about 30 kW/km^2, which is not enough to cater globally for human power needs. In 2013, Rajagopalan and Nihous gave an evaluation of the global resource available via OTEC technology as about 14×10^9 kW.

In this paper, we focus on the very first industrial prototype of an OTEC plant, which is to be implemented off the Martinique Island, located in the French West Indies from 2018 after the preliminary field studies have been completed. Martinique is volcanic with Mount Pelée its largest volcano, which gave its name to the Pelean eruption type, and the Pitons du Carbet, the earlier volcano generated by the same geological hotspot. Martinique is known to have the most severe eruptions, earthquakes and tsunamis recorded in the West Indies. It is also an island characterized by socio-economic indicators similar to those of developed territories in the Human Development Indicator (HDI) (AREC, 2012ab).

For islands like Martinique, OTEC is an opportunity to limit dependence on imported fuel which is the chief source of power on such islands. The lack of power connectivity means that they are strategically dependent on fuel importation, its producers and its transporters. Seawater is a non-speculative resource, because it is local and unlimited.

Furthermore, deep-water pumping could affect the environment of the OTEC power plant (see "OTEC: operating principle"). The task of evaluating this effect is mainly taken by the Hawaii marine science pole, to which scientists provide the most of the data on this subject (Harrison 1987; Nihous 2005and 2007; Jiai et al. 2012). The pivotal concern is the effect of the artificial upwelling of both the deep seawater and the surface seawater, and the subsequent threat of the modification of the local seawater temperature, turbidity and oxygenation, and the impacts that can be triggered by those modifications for the marine environment and human activities that depend on it.

OTEC: operating principle

The operating principle of OTEC can be summarized as a heat engine operating between two volumes of water at different temperatures to produce power. The amount of power produced is temperature difference dependent (Vega 2012). The techniques used for heat transfer fall into two categories: "open cycle", which uses the seawater itself, (Claude, circa 1930) and "closed cycle" which uses other liquids (Andersen, circa 1963) such as propane, Freon, ammonia, the latter being potentially mixed with water and, recently for OTEC, HFC refrigerants 245fa (Morisaki and Ikegami 2012) and R134a (Semmari et al. 2012). The water temperature difference is used to evaporate and condense the heat transfer fluid (Fig. 1). The surface water evaporates it, producing a vapour pressure, which drives the power turbine, and the cold water then condenses the vapour, regenerating the liquid phase. This

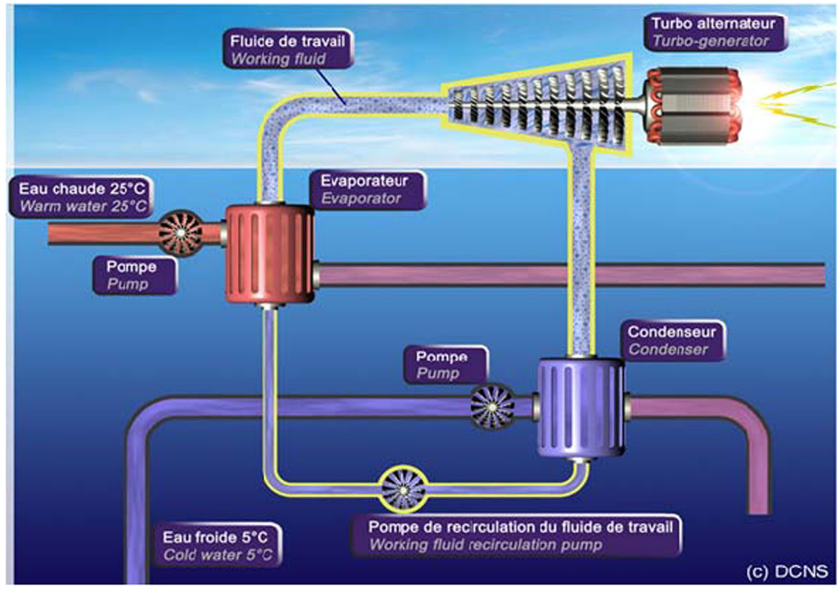

Fig. 1 OTEC operating principle. *Yellow-highlighted circuit* corresponds to closed cycle. Figure provided by DCNS

is an application of Carnot cycle (Carnot 1824). Indeed, the OTEC yield is directly dependent on the heat transfer fluid and turbine performance, involving the Rankine cycle (e.g. Dugger 1975), the Kalina cycle (Uehara and Ikegami 1993) and the Uehara cycle (Ikegami and Uehara 1994).

The open cycle involves seawater evaporation under partial vacuum. The yield is low (about 0.5% of the seawater is vaporized), but seawater is unlimited. The evaporation and condensation provide freshwater in a process of desalination. After the process, seawater could be released into the sea because of the low temperature depletion—proportional to the yield. The closed cycle involves an environmentally friendly and yet potentially hazardous trace heat transfer fluid which has better performances than seawater: a Carnot cycle theoretical energetic yield which could attain about 6.7% of the optimal thermal efficiency (Berger and Berger 1986). In 1993 (Uehara and Ikegami), an operative thermal efficiency of 5% was attained. Initiating and drive strength are not taken into account, neither are the economic aspects, i.e. development, building and maintenance. On the one hand, the larger the OTEC installation, the more profitable the plant. But on the other hand, building a very large OTEC plant is a less flexible strategy and could lead to power overproduction, considering the tropical insular power needs. One hundred-megawatt net power generation plants are profitable (Worrall and Hurtt 2010). Demonstrators are actually designed for 10 MW—but profitability could be attained, thanks to the incentive of public renewable grants and carbon trading. Pumping cold deep water consumes 25% of the power produced.

Comparing the 40% yield reached by conventional fuel-fired electric power stations, OTEC does not follow the same paradigm as its production is totally independent of fuel costs or economic yield because it is offset by low running costs, which are limited to site maintenance, instead of being dependent on a purchased, non-renewable, non-sustainable, speculative and strategic fuel (Plocek et al. 2009). Authors will not focus on economic concerns. For details, see Vega 1992 and 2010.

OTEC minimum operating requirements

OTEC needs warm water. Such warm water could be obtained by capture of warm industrial effluent, since Claude (1928) using blast furnace effluents to Kim et al. (2009), using nuclear plant effluent. By deploying OTEC prototypes in tropical areas, warm surface water is easily available as is cold deep seawater, thus providing the necessary resources for OTEC which in high latitudes is practically impossible (Nihous 2007)—for high latitudes, using warm industrial effluents is more pertinent. Thus, prototypes where deployed (or are expected to be) on warm seawater, like Cuba, Brazil, India, Hawaii, China, Indian Ocean and Japan Sea. The difference in temperature between the two water volumes should in fact be of about 20 °C, but if abyssal deep water is regarded as an unlimited stock at about 4 °C, then cold water could be expected to be found whatever the location of the OTEC plant, thus surface water would be the limiting parameter. Indeed, tropical open oceanic areas, like Indonesian and Polynesian areas, and confined seas away from cold surface streams, like Caribbean Sea, Red Sea and, to a lesser extent, Eastern Mediterranean Sea, present enough sea surface temperature to apply OTEC technology (Fig. 2): even if such thermic dependence limits OTEC extension, the terrestrial geothermal alternative based on warm springs is at least as limiting. Moreover, OTEC is especially pertinent for supplying coastal needs, thus limiting power line loss and bearing in mind that

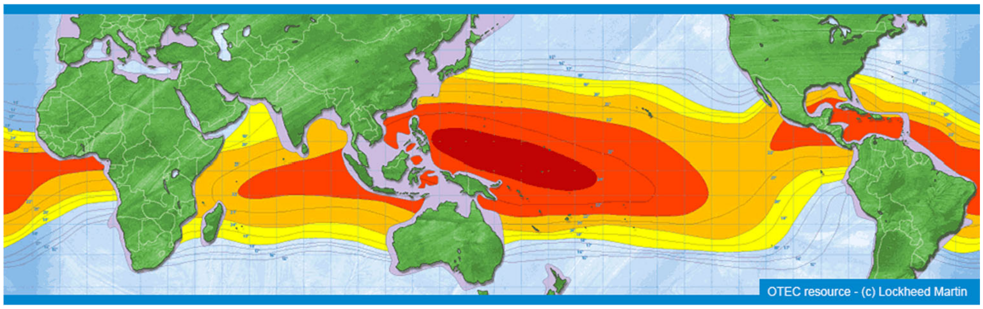

Fig. 2 Map of OTEC deployment propitiousness. Average of monthly difference between surface seawater temperature and deep seawater less than 18 (*blue area*), between 18 and 20 (*yellow area*), between 20 and 22 (*orange area*), between 22 and 24 (*low red area*) and greater than 24 °C (*crude red area*). *Purple area*: water depth less than 1000 m (OTEC may be feasible in this location). Image credit: Lockheed Martin composition, DOE data

the human population aggregates in the 100-km coastal belt (Haslett 2009).

An OTEC plant could be land based or floating. In those two cases, OTEC needs three pipes or strainers: one intake pipe to suck in cold seawater, one intake pipe to suck in warm seawater and one for the mixed effluent. However, the land-based OTEC version implies that the core apparatus, like pumping devices, condenser, evaporator, working fluid and its recirculation pump, are located on the shoreline as opposed to floating version for which the core apparatus is placed on board a special ship or platform. For the land-based version, the pipes and strainers lie on the bottom whereas they are suspended beneath the hull of the floating version wherever the apparatus is located.

The Caribbean Sea is one of the warmest seas in the world, because of the tropical position, the limited freshwater input and the relative confinement, thus leading to a notable water stratification (Jones and Leach 1999 and other authors). In such a case, the appropriately cold deep water could be sucked into the intake pipe at bathypelagic depth (about 1000 m deep). The mixed effluent at about −100 to −200 m deep in order to avoid short-circuiting the warm surface water which is being sucked into the warm water circuit. Alternatives to fossil fuel are limited, and the Caribbean coast of the West Indies is marked by a short continental shelf then a steep continental slope. It is a favourable disposition for OTEC deployment.

However, the Caribbean Islands' biodiversity is rich but has already undergone harsh mistreatments: erosion, coastal ecotone depletion (mangrove-seagrass-corals), chemical and debris pollutions and is indeed endangered.

Possible damages induced by OTEC deployment and functioning

OTEC plants could be deployed as either floating platforms or land-based plants. A floating OTEC platform could be likened, in area, to a shore-distant small-sized cargo ship (70 m length, 30 m width). Land-based ones have the dimension of handball pitch. Incidentally, an OTEC plant does not threaten the landscape and the floating version could be a solution for very confined coastal territories.

Damage involved around OTEC installations is mainly a cause of concern for the biota, for both the land-based and for the floating version. Notwithstanding the initial building works which will lead to the alteration of the sea bed, the OTEC routine activity involves the input of bottom water which is thermally tepid and with depleted oxygen content, the power production itself—and its transfer to the coast for floating OTEC installations—must be taken into account. Each deployment type exposes the environment to specific hazards. The impact of OTEC effluent could be due to (1) artificial upwelling of deep water with different temperature, nutrient and oxygen contents, turbidity, salinity than the seawater layer's one into which it will be introduced; (2) the functioning noise and (3) electromagnetic field. The aim of OTEC implementation studies was to determine if such hazards could significantly impact the marine environment and the related human activities.

Building impact

Regardless of the OTEC deployment type, it is necessary to bury the cold water intake suction pipes and effluent pipes (land-based OTEC) as is the case for the submarine electrical power cable at landing point (floating OTEC). Even if pipes and cable differ significantly in size, the trench needed should be dug between admission and emission depth for pipes and −200 to −30 m depth for the cable, −30 m deep for a minimal buried section. The depth implies that directional drilling should be performed between surface and −30 m. Otherwise, the trench could reach the shoreline. Considering the diameter of each pipe or cable, the corresponding width will differ but is of the order of few of meters (Fig. 3). However, this action involves the total and immediate destruction of the sea bed and, depending upon the nature of the sea bed, suspended matter impact should be taken into account considering the extreme vulnerability of corals to erosion. Thus, high-endemic endangered species hotspots and especially confined ones, i.e. coves, are inappropriate for OTEC deployment, whatever the deployment type.

Land-based OTEC

For the land-based OTEC installations, it is necessary that all the pipes be connected to the shore, i.e. the cold deep-water pipe, the warm surface water one and the mixed water one. Each pipe, the diameter of which will be of the order of 1 m, involves digging a trench in the sea bed, a step that will destroy that part of the sea bed. Moreover, the volume of sediment lifted due to the digging could be expected to be greater than that of a floating OTEC platform. The tropical benthic biocoenosis involving corals, which are very turbidity vulnerable, would lead to a severe degradation of local fauna.

In the case of a coral barrier reef, the risk of drilling an open trench through the barrier would lead to a severe degradation of the coral barrier reef.

Floating OTEC

The floating OTEC installation needs to be anchored but at great depth because of the 1 km deep cold water suction pipe. Thus, the floating OTEC platform should be as close as possible to the shore in order to limit costs and power line loss. Deploying a floating OTEC platform needs a water column of at least 1300 to 1400 m. Obviously, an admission strainer should be used to prevent sediment being sucked in: suspended matter, due to turbid streams or submarine slides, could have severe consequences, thus the importance of preventive measures (Dengler and Wilde 1987).

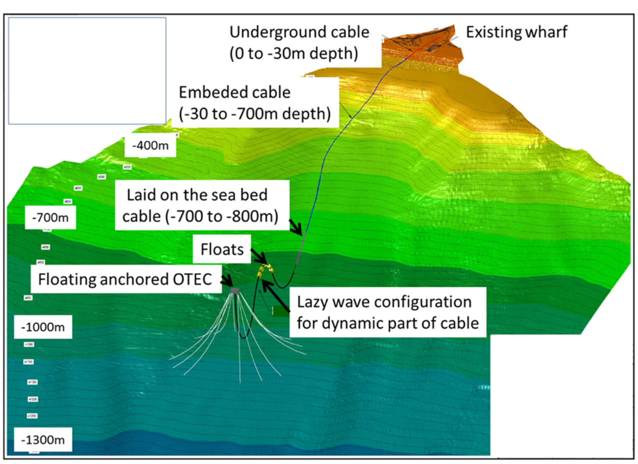

Fig. 3 Layout of OTEC anchoring and connection to the shore

Anchoring is performed at bathypelagic depth with several large anchors and an additional one devoted to controlling the depth of the submarine electrical power cable. Each anchor corresponds to a totally destroyed sea bed area, worsened by the anchor chain sweeping area. However, at such depth, except in the case of a hydrothermal vent, biota density is limited: infra to −1000 m, where no light reaches even if sessile benthos organisms could prosper, they remain scarce because of non-autotrophic species like sponges, crinoids. Although density is low and anchoring damage is limited, it is still a challenge.

Building a floating OTEC could induce significant biota damage because of local benthos destruction. However, such damage could be reversible: the solid or naked structures could be secondarily colonized and the OTEC deployment site has been specifically defined, i.e. not on hydrothermal area, not in a cove which could confine the suspended matters generated by digging, damage to biota due to OTEC could be considered as limited and reversible.

Functioning impact

Three types of threat should be considered for OTEC: the impact of low-oxygenated tepid effluent, the noise level and the electromagnetic field, but they depend upon their shape, or their magnitude, and the deployment type. Another OTEC consequence for bathypelagic biota is the risk of being sucked into the intake pipe. In this way, the Hawaii plant reported the sucking in of bathypelagic plankton and micronecton due to the stream generated into the strainer (Harrison 1987). Pressure decrease with the depth decrease could be lethal for deep biota—but passing through the turbine is undoubtedly lethal. Incidentally, effluent is enriched by nutrients due to deep water but also to hacked up animals which have passed through the turbine. However, the OTEC rate of flow induced only very local consequences (Jiai et al. 2012). Notwithstanding, Rajagopalan and Nihous (2013) modelled the effect of the full exploitation of the OTEC potential and warned that the oceanic surface layer would cool down, an effect produced in tropical OTEC regions with a compensating warming trend elsewhere worsened by thermohaline circulation boost, leading to an oceanic stream disequilibrium during a 100- to 1000-year period. However, limiting OTEC exploitation to 7 × 109 kW, corresponding to the half of the global OTEC potential, is benign on a global scale.

Land-based OTEC

A land-based OTEC installation does not present any electromagnetic hazard because of the direct connection to the land based power distribution network to consumers.

Noise could be due to suction because of the pipe length. However, the land suction pump for cold water would not be audible a few miles away. Pipe vibration due to work could generate a low-frequency sound and low noise (Auvray et al. 2012a).

However, a land-based OTEC plant involves the emission of mixed effluent constituted by nutrient-rich and low-oxygen deep water and the oxygenated but nutrient-poor surface water. Effluent, even if the pipe nozzle is as deep as for the floating OTEC platform, will be close to the bottom and lead the benthos to a maximal exposure to tedious, low-oxygenated water and potentially nutrient-rich conditions. Depending on the depth of effluent emission, temperature could be close to that of the surrounding seawater and with the same salinity. Such isotherm and isohaline water would nevertheless be oxygen depleted and CO_2 rich. Depending on the OTEC model, the mixed water effluent nozzle for a floating OTEC is −15 to −200 m deep and the water shoot is vertically buffered after 10 to 80 m, leading to a −25 to −280 m depth plume effluent. DOE (1981, cited in Harrison 1987) estimates the outlet nozzle depth at about −100 m but opportunely considered the plume as flowing out to sea.

However, coastal streams are rarely off directed when not freshwater driven, estuary surroundings are not propitious for OTEC technology, which needs stable marine stratification but such streams are mainly parallel to the coast or are tide commuting. Thus, the effluent plume could be considered as partially folded along the coast, exposing biota, especially turbidity-vulnerable ones; and this effect would be worsen on indented coastline further limiting dilution. The report by Harrison (1987) is clear about the coastal fauna alteration by land-based OTEC installations: “a major impact especially for sessile species”.

Seawater is limpid especially in intertropical area; the photic zone deepest limit, and the euphotic zone, reaches a great depth (about −200 m), strengthening tropical primary productivity (Krause et al. 2011). Some of autotrophic algae are in endosymbiosis with coral so the benthic biota is abundant and biodiversity hotspots are common. Their primary production could be severely altered by a temperature increase and the coral thus endangered (Goulet 2006). Inversely, diffusing the plume too close to the surface in order to cool the seawater could locally contravene coral bleaching and allow aquaculture (Werner 1981 and followers). Hypoxic conditions could affect them considering that endosymbiosis does not occur during the night (Höffle et al. 2012). Nutrients could increase such patterns by direct organic matter decomposition and eutrophication, especially in tropical oligotrophic biotope (Tortell et al. 1999) and this potentially in addition to coastal nutrient input (industrial of domestic wastewater, altered river). Moreover, coral is highly vulnerable to turbidity and a pipe close to the sea bed could obviously suspend sediment. Impact on fisheries could be significant because planktonic communities could be modified because of temperature increase (David et al. 2007).

Floating OTEC

At the same distance from the shore and the sea bed, a floating OTEC platform minimizes the effluent effect because of three-dimensional dilution.

An effluent plume with a density different from its surrounding will rise (if light) or sink (if dense) in the water column, and entrain ambient water along its path until it reaches a depth of neutral buoyancy; then, the stabilized plume spreads laterally and vertically through advective and diffusive processes. The entrainment process modifies the plume characteristics (temperature, salinity, etc.) and determines the depth of its neutral buoyancy. In the case of Martinique case study, the effluent plume buoyancy is expected to be mainly driven by temperature because of the lack of salinity difference depending depth (Fig. 8 and Auvray et al. 2012a), moreover regarding the temperature differences in parallel (Fig. 7). The outgoing stream pumping downward is designed for leading to a rapid reaching of neutral buoyancy. Nutrient input in open sea could increase primary production (Yoza et al. 2010; Joubert et al. 2011) or favour detriticolous animals, but the volumes involved would not justify bloom (Menesguen et al. 1989). Notwithstanding, the impact of low-oxygenated deep water is the more difficult impact to assess: Jiai et al. (2012) highlighted how effluent discharge could modify seawater characteristics nearby or at a distance from the OTEC plant. The sediment suspension risk is null.

The noise generated by a floating OTEC plant in operation, considering prototypes, is close to the noise of a cargo ship moving slowly. Considering the acoustic impact assessment, the sound could be audible over a few kilometres but never be injurious for marine mammals, despite their proximity to the OTEC sound source (Ducatel et al. 2013).

Considering the electromagnetic field, specific simulations devoted to the Martinique project are not sufficiently consistent for publication. Setting up an OTEC installation is a long process, whatever the swiftness and the experience of study teams involved. The effect of electromagnetic field is expected mainly on mammals, i.e. alteration of swimming and sense of direction (Balmori 2015), anxiety (Lee and Yang 2014) leading to reprotoxicity (Krylov 2010).

Considering all offshore OTEC elements, antifouling will be required.

The Martinique case study

The Caribbean Sea, previously presented, is one of the most propitious for an OTEC plant. The Martinique regional authority, in partnership with Direction des Constructions Navales Services (DCNS), will oversee the floating OTEC installation on this shore designed for both experimentation and production.

On the European Union level and under their jurisdiction, Martinique is one of the Ultra Peripheral Regions. As such, Martinique benefits from a specific energy program in order to reach energy autonomy and perform its energy transition.

Indeed, in view of achieving the energy transition, the European Union directs its energy policy towards the transition to reduce the use of non-renewable energy and reduce the production of greenhouse gases. The EU's outermost regions belong to either France (Martinique, Guadeloupe, French Guiana, Reunion), Spain (Canary Islands) or Portugal (Madeira and the Azores). Table 3 shows that the energy based on the thermal gradient of the sea could be profitably implemented in Martinique and Guadeloupe (see Modeling Study for the Exploitation of Marine Resources for Electricity Generation in the Outermost Regions expert report produced as part of the ERDF program for the outermost regions, NRJRUPplus 2007).

France has chosen, in its energy policy, to reduce the energy production from non-renewable energy since 2007. The French laws concerning power supplies were adapted to the French overseas territories. Thus, Article 46 of the Grenelle I law describes the specific provisions applied to overseas territories. There are particular statements to achieve energy independence, including a 50% share of renewable energy in their consumption in the overseas territories—such as Martinique—and 30% in the case of Mayotte, from 2020. In 2016, these goals are still far from being achieved, so the French government supports projects in favour of energy independence based on renewable energy (Galenon 2011).

In order to reach those goals, the regional authority of Martinique has to develop wind and solar energy, within the limit of electricity grid acceptability, and has to develop non-intermittent renewable energy sources such as ocean thermal energy and interconnections with the Dominica Island (DEAL Martinique and Région Martinique, 2013). So, the decision to install the floating OTEC plant in Martinique can be largely justified in the national and European legal context.

Martinique overview

Socio-economic and heuristic context

Martinique Island is administratively French in its own right and a fully functional French territory. Since the elections of December 13, 2015, the territory has become the Regional Authority of Martinique (Collectivité Territoriale de la Martinique (CTM) in French), which is a new administrative status. For the moment, this new status does not seem to change the perspectives for the project of a floating OTEC installation. Administrative authorities fully support the OTEC implementation.

As a part of France, Martinique benefits from long-term environmental monitoring. For example, the Water Framework Directive was enforced immediately by the environmental authorities with some adaptations. For decades, the administrative teams overseeing the Martinique marine environment have benefitted from the assistance of university oceanology labs and private teams of engineering consultants. Moreover, all the French marine institutions, partly or fully focused on the marine environment, are also located in the French West Indies, and particularly, in Martinique (Ifremer, IRD, CNRS, etc.). Moreover, a dense network of environmental associations supported by civil societies is implicated in environmental concerns. In this way, environmental issues receive much consideration.

Population density of the West Indies in general is both critical and growing (Table 1), leading to increased power needs. Martinique with a population of just under 400,000 inhabitants and Guadeloupe Islands have two of the largest populations in the Lesser Antilles; and whereas, their annual economic growth rate is low in comparison with the other islands of this Caribbean zone, their need for energy is increasing. Economic growth has been negative in Martinique in recent years (IEDOM 2015a; INSEE 2015). The gross domestic product per inhabitant is about 21,000€, outstripping the islands of the West Indies (Bahamas: around 20,000 €; Barbados: about 5000 €), except for the French territory of Saint-Barthélémy (35,700 €) (IEDOM 2015b) and Puerto Rico with its commonwealth status with the USA (close to 27,000 €). The comparison of the Human Development Index (HDI), which is a more complete indicator, confirms also that Martinique has a high HDI in comparison with the other islands of the Lesser Antilles, highlighting the socio-economic inequalities (AREC 2012a, b). In other words, if we consider the standard of living in the non-French territories, it is inferior to those of the French overseas territories and to those of the western world and this is reflected also in their level of related scientific marine knowledge. Martinique, on the other hand, enjoys a western standard of living and an environmental awareness is emerging which makes the installation of a renewable energy plant more plausible.

However, despite the environmental investigations performed in French West Indies supported by French public and private grants, the environmental sciences are strikingly lacking, especially in the fields of biodiversity and currentology. For example, for the Fort-de-France international port extension, Gaela and Ferry (2015) described five unknown cnidarian species were identified in a 1.3-ha coral reef directly adjoining the port, in the inner part of the Fort-de-France Bay, in central Martinique shore, though the most frequently studied place of Martinique.

If such a report could be written for Martinique, it is obvious that the other places worldwide where OTEC could be implanted, risk being totally unaware to an even greater extent of their biodiversity. However, in order to know the effect of a floating OTEC, a sufficient biodiversity inventory is needed.

Table 1 Population, density (h/km^2), surface area (km^2), annual rate of increase (%) and last census date of Caribbean islands, ordered from the north-west to the south-east extremities of the archipelagos arc

Caribbean main islands	Density (h/km^2)	Surface area (km^2)	Population	Annual rate of increase (%); year[e]	Last census date
Cuba	102	109,884	11,167,325	−0.12; 2012	2012
Haiti	364	27,750	8,373,750[a]	1.45; 2015	2003
Dominican Republic	78	48,730	9,445,281	1.42; 2015	2010
Jamaica	268	10,991	2,950,910[b]	1.15; 2015	2011
Porto Rico	430	8870	3,680,472	−0,05; 2015	2010
US Virgin Islands	304	304	106,415	0.23; 2015	2010
Anguilla	180	91	16,418	2.03; 2015	2011
Saint Barthélemy[c]	330	24	9417	2.7; [g]	2013
Saint Martin[c]	665	54	35,594	2.1; [f]	2013
Saint Kitts and Nevis	149	261	51,936	0.76; 2015	2011
Antigua and Barbuda	209	442	92,436	1.24; 2015	2011
Montserrat	92	102	5241	0.5; 2015	2001
Guadeloupe[c]	247	1628	410,335	0.3; 2011[h]	2012
Dominica	98	751	73,607	0.46; 2015	2011
Martinique[c]	355	1128	391,837	−0.5; 2014	2013
Saint Lucia	266	616	163,922	0.74; 2015	2010
Barbados	662	431	277,821	0.31; 2015	2010
Saint Vincent	314	389	102,627	−0.28; 2015	2010
Grenada	260	344	110,674	0.48; 2015	2011
Trinidad and Tobago	212	5128	1,222,363	−0.13; 2015	2011
Margarita[d]	427	1150	491,610	2.8; 2011	2011
Curaçao	335	444	150,563	0.43; 2015	2011

Source: source: official website of census of each country

[a] Estimation of population of Haiti in 2015: 10,110,007 (source: http://www.statistiques-mondiales.com/haiti.htm)

[b] Data from http://www.statistiques-mondiales.com, http://worldpopulationreview.com/countries, https://www.cia.gov/library/publications/the-world-factbook/rankorder/2119rank.html, http://www.caricomstats.org/Demography.html

[c] Martinique, Guadeloupe, Saint Barthélémy and Saint Martin are French territories

[d] Margarita is an island belonging to the Nueva Esparta's State of the Bolivarian Republic of Venezuela

[e] http://www.ine.gov.ve/documentos/Demografia/CensodePoblacionyVivienda/pdf/nuevaesparta.pdf

[f] Estimations in 2015

[g] http://www.iedom.fr/IMG/pdf/ne289_portrait_panorama_2013_saint-martin.pdf, between 1999 and 2010

[h] http://www.iedom.fr/IMG/pdf/ra2010_saint-barthelemy.pdf, between 1999 and 2008

[i] http://www.iedom.fr/IMG/pdf/ra2011_guadeloupe_reduit_.pdf, between 2007 and 2012

Which raises the question: is it the responsibility of the company providing the floating OTEC installations to make such inventory? In other words, is it up to a private company to bear the responsibility of a long-standing investigation deficiency? The implementation of a floating OTEC installation in Martinique significantly helped to improve the knowledge of the marine environment in the area under study. Notwithstanding the biological inventory needed, one of the acute questions is the availability of local experts in local biodiversity. The creation of this floating OTEC plant calls for the development of the local scientific community who will be expected to relay local civil societies. The initial stages of the floating OTEC plant projects will not last long enough to allow the training of local scientists to take part in the decision making process (Secroun 2016). For Martinique, the 3-year site studies before the decision of implementation were possible because of preexistent local private and associative structures for marine investigation (Auvray et al. 2012a, b). Such structures are scarce in other islands in the Caribbean or other parts of the tropical areas. In this way, it seems highly pertinent to create a virtual scientific platform, able to select local and international experts who can consider scientific topics related to an OTEC implementation (currentology, biodiversity…) and who can be deployed in situ. Such a "task force" should involve the supervision of international institutions like PNUE and UNESCO's

Fig. 4 Location of Bellefontaine power plant and expected location of OTEC plant. *Blue lines*: 63,000 V high-voltage lines

Intergovernmental Oceanographic Commission, associations and other stakeholders from governmental and intergovernmental structures depending on the areas concerned.

The floating OTEC location also calls for the knowledge of deep-water marine environments, i.e. bathyal and abyssal depths. The floating OTEC will be installed at the surface of a 1500-m deep-water column, and the suction strainer will be 1100-m deep. Such investigations need heavy-duty submarine equipment, which is too expensive for private structures. Only public institutions from developed countries could be thus equipped, highlighting the supporting role of such countries for this kind of project. Considering the Martinique case study, the potential for improvement of marine knowledge about biota from the subsurface to sea bed is considerable.

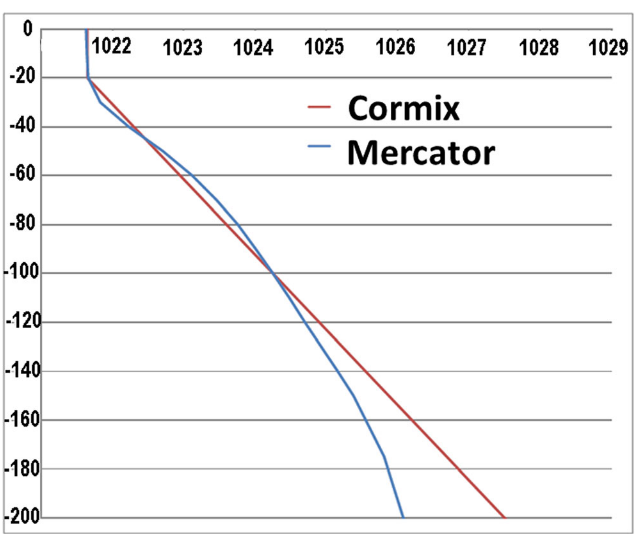

Fig. 5 Comparison of CORMIX and MERCATOR stratification density (kg/m^3) simulation depending to depth

Social acceptance

The project for such an innovating installation was openly detailed to the population in order to ensure the social acceptance of such a floating structure. Some of the obstacles facing social acceptance is the low level of scientific culture, the lack of understanding of the economic importance of the sea, the weak social cohesion including the credibility and representativeness of policy makers. It depends also on the way the public information was diffused; because of the cultural differences, important decisions would have to be detailed via special media (Secroun 2016). In Martinique, the announcement of public meetings to legally inform the public of the project was made through the press and the radio but attendance was very low which would suggest that the diffusion of information to the public had not been a success. The environment authority published an environmental impact file on their website, but it was downloaded a limited number of times (Secroun 2016). Another problem could be the lack of professionalism of local environmental associative structures, considering the way such data was diffused.

For example, in the case of Reunion Island, the political changeover caused the abandon of the OTEC project. In Martinique, the project is still vulnerable to the acceptance (or not) by the population. The agencies promoting the floating OTEC project ran a legal public information campaign to inform the population whereas it would be closer to reality to say that the majority of the population is not aware of the project.

The recent developments towards greater demand for land on the coast are linked the development of the tourist industry in the towns of Carbet and Saint Pierre and around the town of Bellefontaine. Given the spatial extent of the thermic power plant, the tourist industry is underdeveloped, but fishing still plays its role in the dynamics of the labour pool. More and more fishermen are adopting a sociological profile of seasonal workers in the tourist industry, using their fishing boat for sightseeing for tourists, and why not in the future visits to the site of the new floating OTEC plant.

The current energy situation and the consequences of floating OTEC implementation.

The consumption of electricity per inhabitant in Martinique, as in the other French island of Guadeloupe, is higher than in the non-French islands of Lesser Antilles (Table 1). Electrical energy is mainly used for domestic consumption and secondly for service activities including the tourist industry (OMEGA 2015). The major peaks in demand are caused by overconsumption during periods of peak tourist influx (that means from November until April, mostly during Christmas and Carnival holidays).

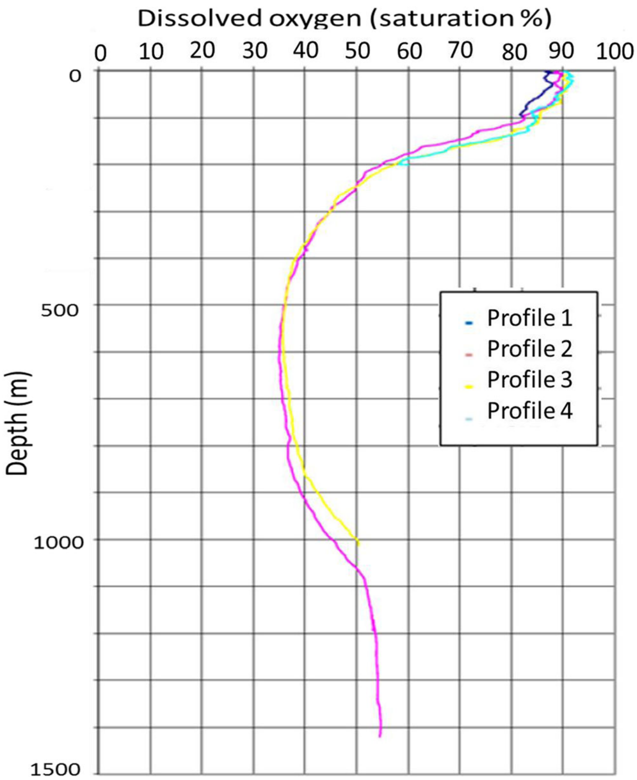

Fig. 6 Dissolved oxygen profile in the water column at expected OTEC plant location (Auvray et al. 2012a)

In the future, the electrical consumption should increase, although Martinique is characterized by an ageing population. Nowadays, the main energy production comes from the Bellefontaine thermic power plant, near the project of floating OTEC, on the Western coast of the island. Currently, the Bellefontaine thermic power plant has a very significant role to play in the energy production of the Martinique Island. The main power lines are from this plant and supply 90% of the power needs of Martinique (Fig. 4). The proximity of this centralized power infrastructure is an essential advantage for the power distribution from the floating OTEC plant. This was a key point in favour of the floating OTEC implementation in Martinique (Autorité Environnementale 2015).

The proportion of renewable energy is very low, around 3% of the total energy production. With the implementation of the floating OTEC plant, it is planned to produce around 16 MW which corresponds to the continuous use by 35,000 equivalent inhabitants (10% of the population).

The Caribbean Sea borders the western shore which slopes steeply down to the bathypelagic level at a depth of 1500 m, which is situated at only 5 km from the shoreline. Fortunately, the Bellefontaine thermic power plant is located on the shore, close to the steepest slopes. Thus, the Bellefontaine power plant provides an efficient relay between the OTEC plant and the insular power network and acts as the co-partner of the power mix on a regional scale.

The Bellefontaine and the planned OTEC sites benefit from the proximity of Fort-de-France Bay because, as Martinique's capital city and naval base for the French navy, the area has been efficiently monitored for a long time. The offshore site is easily accessible by sea for maintenance and the proximity of the Fort-de-France airport in the case of an expert having to be urgently flown in. Fort-de-France power needs could be partially covered by the OTEC platform. However, massive sedimentation occurs in Fort-de-France Bay because of the local extreme erosion and the urban impact on the marine environment is very severe. Inversely, the population of Fort-de-France would have to be protected from industrial hazards due to the floating OTEC site and marine traffic kept consistent, especially cargo ships and ocean liners.

Protecting the OTEC plant from environmental hazards

The next stage of OTEC impact estimation was to determine the local risks that the OTEC plant should be able to endure. Located in a marine, tropical and geological hotspot environment, OTEC installations would have to be protected from tsunamis and hurricane waves.

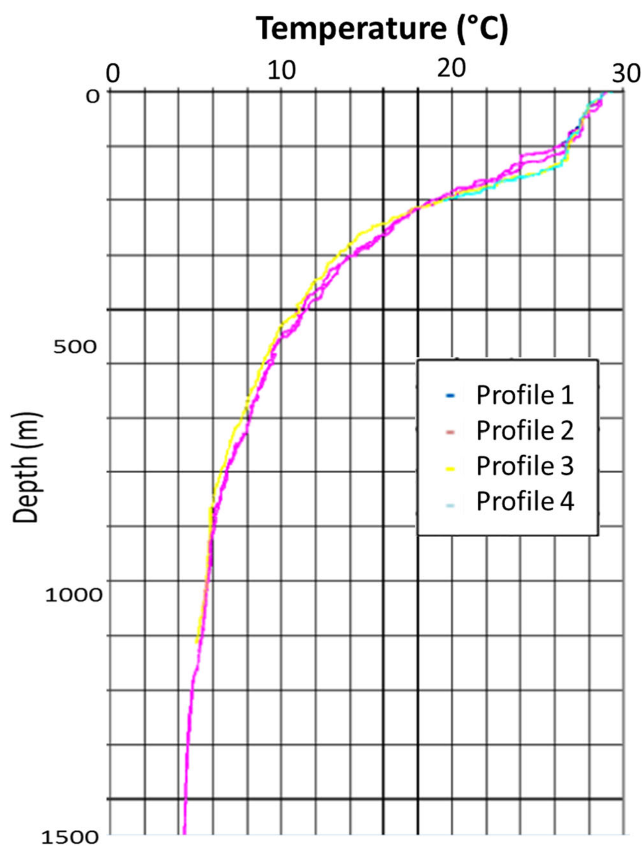

Fig. 7 Temperature (°C) vertical profiles in the location of OTEC (Auvray et al. 2012a)

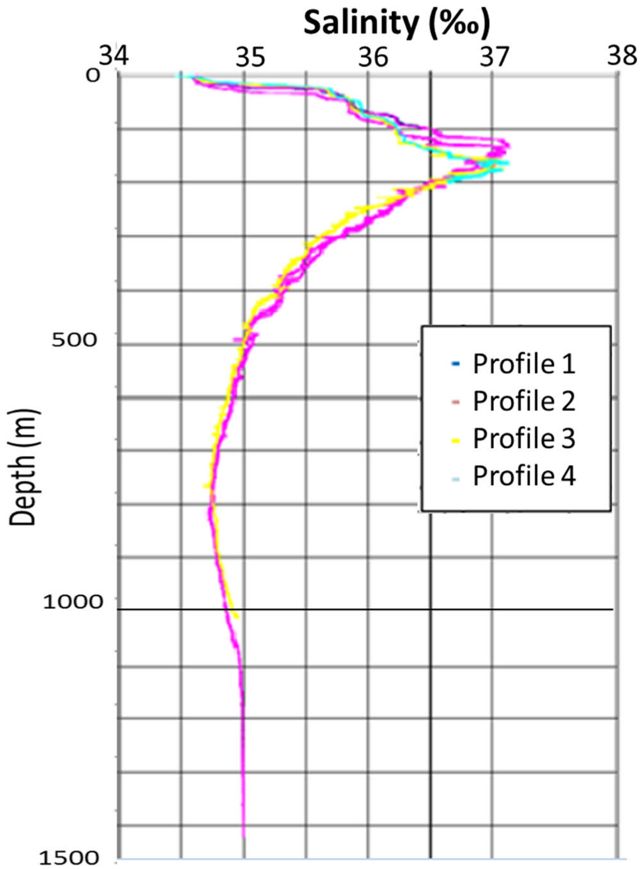

Fig. 8 Salinity (‰) vertical profiles in the location of OTEC (Auvray et al. 2012a)

Indeed, the Caribbean Sea is highly stratified around Martinique, because Amazonian rivers affect the Leeward Antilles. For example, the Amazon and Orinoco rivers provide 20% of the freshwater input to the Caribbean Sea. Their influence (desalination of the 0 to 50 m depth surface water layer) is mainly observable between July and October. The most temperature-stratified period is the winter (26 °C layer of surface water for the depth between 0- and 45-m depth during winter) and the less stratified temperature between May and August when the temperature of the water at depth of 45 m is 1 °C lower than surface water (Auvray et al. 2012a) but when the seawater dilution due to Amazonian rivers is less critical.

Below the depth of 100 m, thermoclines are parallel to the surface (Fig. 11). Between −20 to −250 m, salination (37‰), a subtropical Atlantic stream predominates, then, there is the cool (20 to 7 °C) Labrador stream down to a depth of −750 m. Below −2000 m, the cold Norway stream predominates (4 to 1.5 °C). The inconvenient speed streams mentioned by Dengler and Wilde (1987) seem to have no local equivalent. However, deep streams are not well documented; could OTEC provide an opportunity for more research in this area?

Tsunami waves rise close to the shore, when the depth decreases inducing shortened wave frequency and subsequent increase in amplitude. The consequence is indeed notable mainly very close to the shore and because of marine transgression, which could reach several kilometres inland, e.g. the Fukushima tsunami reached sites 15 km inland (Rao and Lin 2011). Considering the Pacific and Indian Oceans, tsunamis in the Caribbean Sea are not frequent. The Martinique Island would protect the OTEC installations from tsunami waves from the Atlantic Ocean: buffered by the depth, the impact of tsunamis on the planned site is not significant for the floating project. However, such a hazard is very real for land-based sites, because of the coastal disposition of the industrial plant. Moreover, because of the steep slope, landslides are indirectly real hazards for land-based plants (a landslide on the site is theoretically impossible) but indirectly (a landslide could dam the river and thus produce a piston effect).

Hurricane waves are huge conventional waves. Wind records have been kept by Météo-France since 1995, and waves have been monitored for the last 35 years, and especially during extreme events. The Caribbean Sea is rarely affected by 0.5-m high waves, under the dynamic fetch generated by trade winds. Atlantic waves are buffered by the shadow effect of the Martinique Island. The worst conditions, i.e. 8-m waves in the Atlantic oriented 120° N, would increase waves at the site by only 0.8 m in height Thus, 1-m high waves occur during about 10% of the year, and wave of 1.5 m high or more occurs during 1.5 days per year. Barbadian or Cap-Verdean hurricanes are indeed weak—but hurricanes from the inner Caribbean Sea, like the Lenny hurricane, are more dangerous: the waves at the future OTEC site during the Lenny event were estimated at 3.5 m high. Centurial waves are of lesser magnitude than in the Atlantic, where they are estimated at 10 m high. NAH estimates them at about 8.5 m high and Météo-France estimates them at about 6 m high—based on 35 years of monitoring whereas NAH bases their data only on 11 years of monitoring. The highest wave monitored (August 17, 2007, strengthened by the hurricane, during Dean Hurricane off Santa Lucia) reached 13.3 m high. Including headroom, a floating OTEC should be able to endure a 13.4-m high wave. The floating OTEC projected plant is designed to endure such waves.

On the contrary, the land-based OTEC installations are vulnerable to hurricane conditions, combining tropical rain to the landslide risk. The Bellefontaine plant site is a very deep valley.

Floating deployment for our OTEC installations would prevent the main marine hazards, which is not the case for the land-based OTEC plant, anthropic risks excepted.

Protection of the environment from OTEC hazards

As previously described, OTEC hazards could be due to

An exchanger out sealing accident due to the collision between a large ship and the floating OTEC plant, or vandalism,

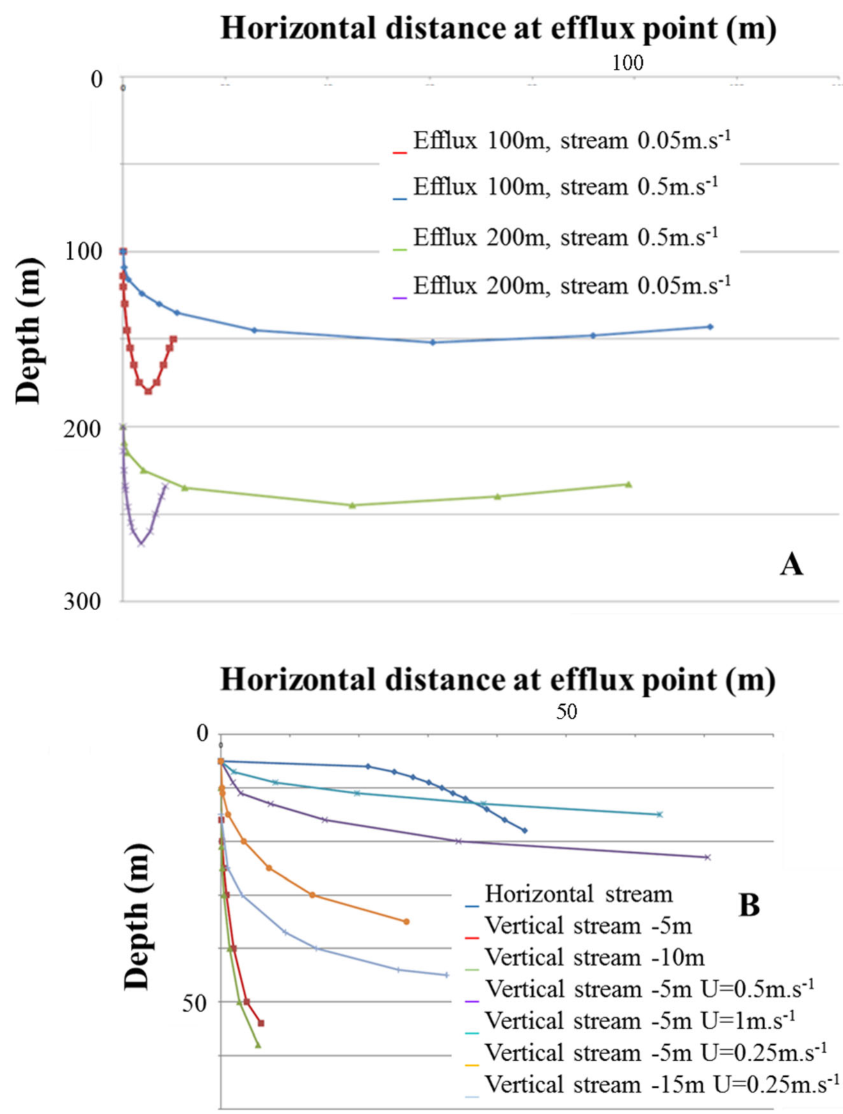

Fig. 9 Comparison of simulation results depending to efflux depth and efflux depth, velocity and direction. **a** Depending to efflux depth and direction, for cold water efflux. **b** Depending to velocity and depth direction, for warm water efflux

including terrorism at either type of plant, either of which could fissure even smash the closed OTEC heat transfer fluid tank. Ammonia is a highly toxic, flammable, anaesthetic and asphyxiating gas, which could leak from the plant.

Bellefontaine is located in a very steep and narrow valley which is poorly ventilated because of the proximity of the Pitons du Carbet mountain, and the escape routes that are limited for the Bellefontaine town inhabitants should there be an ammonia leak on the land-based plant.

Considering the Martinique layout, continuous trade winds should carry the gas westward, i.e. out to sea. With regard to the floating OTEC platform, the distance from the shore limits accessibility, which is pivotal data for both OTEC and population safety. The OTEC platform, at a distance of 5.3 km from shore, should preserve Martinique's population and biota since 5.3 km of open sea is enough to dissuade most onlookers, and is too far for swimmers, and small craft. If vandalism is expected, a 5.3-km stretch of sea could facilitate intrusion alert. Considering land-based OTEC installations, vandalism or intrusion would be significantly easier. Direct population exposure to a gas cloud is a possible threat and would lead, in compliance with local legislation, to Seveso 2 classification (Journal Officiel 2012).

Should an ammonia leak occur, prevailing trade wind regime would drive the ammonia slick seaward and not towards the Martinique shore. There is no land westward of Martinique as far as 2500-km distant Nicaraguan shores, a useful distance for alerting its population and slick dispersal by the wind. The unpredictable wind cone could include the 1000 km distant very North coast of Venezuela.

Moreover, ammonia is a widely used gas worldwide and the corresponding safety procedures are well known.

Effluent impact is less spectacular and very likely to be a potentially silent, invisible and yet serious threat. The impact of OTEC plant effluents has been under study for a long time—the goal of the "Mini OTEC" deployed by NEHLA

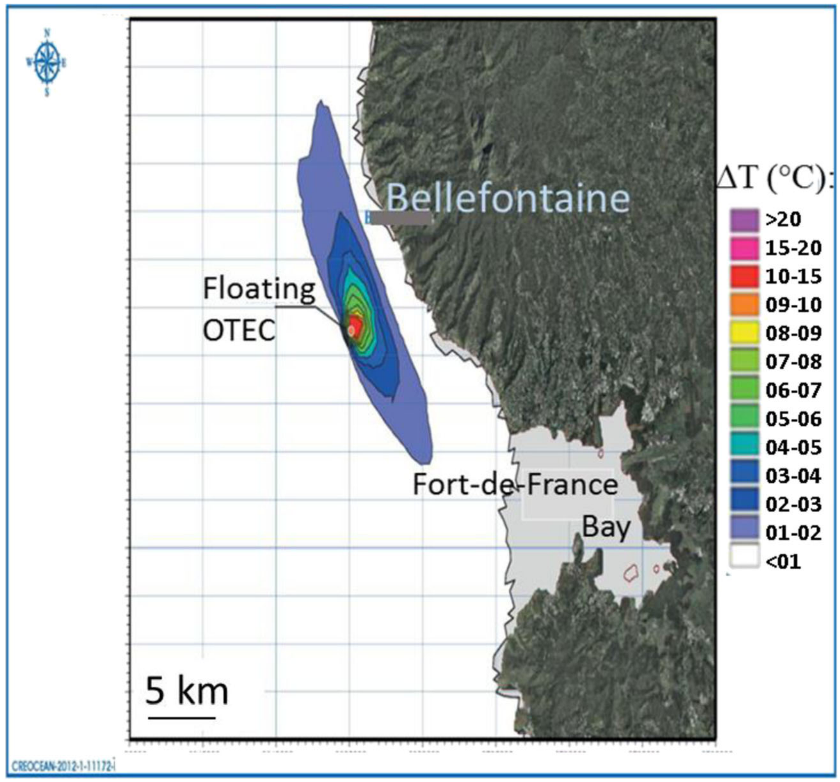

Fig. 10 Simulation of horizontal extend of temperature difference at 150 m depth for a 100,000 $m^3 h^{-1}$, 8 °C water efflux in 25.5 °C water

off Hawaii was only to assess the environmental impact of the OTEC plant. Indeed, OTEC effluent, nutrient enriched by depth nutrient and animal detritus from animals sucked into the OTEC turbine but O_2 depleted, could affect the biota (Jiai et al. 2012). Obviously, such an impact would depend on the plume dilution of effluent.

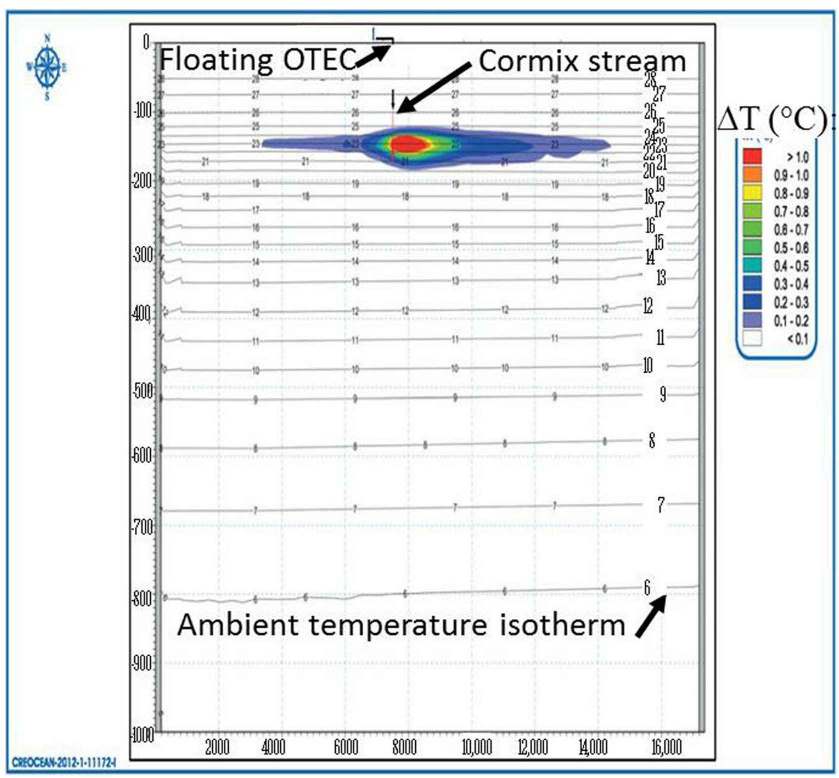

Fig. 11 Simulation of vertical extend of temperature difference at 150 m depth for a 100,000 $m^3 h^{-1}$, 8 °C water efflux in 25.5 °C water

Table 2 Dilution plume of the floating OTEC project, with length meridian oriented and width longitude oriented

Marine stream condition	Usual	Usual	Weak	Strong	Moder.	Usual	Usual	Usual	Usual	Weak
Executory depth (m)	50	50	50	50	50	50	50	100	100	100
Effluent temp/ocean temp (°C)	8/27	8/27.5	8/28	8/27	8/27.5	8/27	15.8/27	8/24	8/25	8/25.5
Impact depth (m)	100	100	100	100	100	100	100	150	150	150
Effluent flow rate (100,000 m^3/h)	100	100	100	100	100	25	200	100	100	100
Maximal extend—length (km) parallel to the shore	10.5	10.5	12.4	0.0	12.8	1.0	10.0	10.0	12.4	20,4
Maximal extend—width (km) perpendicular to the shore	2.4	2.9	5.2	0.0	3.3	1.0	1.9	1.9	2.9	4.3
Minimal distance to the shore (km)	3.8	3.8	3.3	5.7	3.3	4.8	3.8	3.3	4.3	2.4

The extent correspond to 1% limit, i.e. the subsurface area where water characteristic during OTEC functioning will differ less than 1% from initial conditions

Moder. moderate

The efflux impact could be due to (1) the artificial upwelling and (2) the consequences of antifouling.

(1) The effect of the off shore OTEC plant in Martinique coastal area has been investigated by DCNS in partnership with AKUO ENERGY (which will exploit the floating OTEC) in order to determine the consequences of the artificial upwelling of 100, 000 m^3/h.

Such an impact has been investigated on two previous occasions:

– DCNS, in partnership with AKUO ENERGY, investigated or had naturalists and oceanographers investigate to evaluate, respectively, (1) the environmental impact of the OTEC plant on the shoreline and the coastal land surfaces and (2) the dilution plume due to OTEC activity. Oceanographers studied the vertical profile of waters from the sediment bottom to the sea surface at the planned location of the floating OTEC site. Those data were compiled in a confidential report that DCNS and the Martinique Territorial Authority were allowed to be partially declassified for the purpose of the present publication alone. The investigation by DCNS was performed in order to determine the water stratification (Fig. 5), the dissolved oxygen content (Fig. 6), the temperature (Fig. 7) and the salinity (Fig. 8) throughout the 1500-m water column (Auvray et al. 2012a).
– France Energies Marines, in accordance with DCNS, but performed independently, worked on the biological impact and, incidentally, confirmed the dissolved oxygen content, the temperature and the salinity profiles and completed it by the chlorophyll-a and NO_3, a nutrient, content and the light incidence. This study, named IMPALA, was led by Giraud et al. (2016), and complementary profiles were published in Boye et al. 2015. Biological impact was assessed by combination of deep-water content and surface condition, following a protocol detailed in the related article.

DCNS, AKUO ENERGY and France Energies Marines investigation led to some pivotal conclusions:

– If the expected temperature and light incidence, i.e. photosynthetically active radiation (PAR), decreases are confirmed, the other parameters of the water column are less intuitive. (1) The dissolved oxygen content does not decrease linearly with depth. Considering the depth at which bottom water will be pumped, it is assumed that the

Table 3 Preliminary economical and geographical synthesis about potentiality of electrical production in the Ultra Peripheral Regions of the European Union

	Swell		Ocean thermic gradient		Wind		Current and tide	
	Resource	Potentiality synthesis	Resource	Potentiality synthesis	Resource	Potentiality synthesis	Resource	Potentiality synthesis
Martinique	Average to weak	Good (75–80%)	Very strong	Extremely good (80–90%)	Average	Good (50–80%)	Unsufficient	Null
Guadeloupe	Average to weak	Good (60%)	Very strong	Extremely good (80–90%)	Average	Good (50–80%)	Unsufficient	Null
Guyane	Average to weak	Average to weak	Average	Average (40–60%)	Unsufficient	Good to strong (50–80%)	Unsufficient	Null
Reunion	Strong	Very good (75–90%)	Average	Average (40–60%)	Average to strong	Very good (50–90%)	Unsufficient	Null
Canary Islands	Average to strong	Extremely good (75–100%)	Unsufficient	Null	Average to strong	Very good (50–90%)	Unsufficient	Null
Madeira	Very strong	Extremely good (75–100%)	Unsufficient	Null	Strong	Very good (50–90%)	Unsufficient	Null
Azores	Very strong	Very good (75–85%)	Unsufficient	Null	Strong to extremely strong	Very good (50–90%)	Unsufficient	Null

Source: NRJRUPplus (2007)

dissolved oxygen content is at, worst, half of that at the surface and could reach a higher value than at the surface. (2) After a higher salinity layer between −50 to −400 m, the salinity in bathyal layers was similar to that at the surface. (3) Chlorophyll-a content show an optima around −100 m depth (Giraud et al. 2016). Phytoplankton is still present in photic areas, but the NO_3^- increase and other water parameters are propitious to primary production; (4) nutrient content, according to Boye et al. (2015), increases from the surface to the −800 m depth, then NO_3^- content seems to be stable. In other words, the mixed efflux water from OTEC plant (1) will not modify the PAR, (2) will be colder than ambient water (but, due to hydrodynamic patterns and efflux direction, temperature will lead the efflux water to the water layer with the same density, including temperature and salinity, (3) salinity of the receptive water will be higher than efflux water, i.e. the dilution plume, primarily pointing downward on the chart, will correct its trajectory to the isobaric layer because of its positive buoyancy as shown in Fig. 9, (5) artificial upwelling will occur in the fluorescence peak depth, introducing too high a NO_3^- content, i.e. could increase the primary production but could introduce bathyal plankton. However, such introduction is dependent on the OTEC heat exchanger, due to the size of the exchange surfaces which will operate like a filter, creating during the transfer through the device mechanical strains on plankton biota. Such biota can resist sustentation in the water column, including low mechanical resistance even gelatinous compartments. Due to the lack of knowledge about bathyal plankton, it is impossible to exclude the introduction of such species (whatever their stage of development) in the considered −100- to −200-m layer but it is easy to conjecture that crossing the OTEC heat exchanger will be an extremely selective step. Moreover, the adaptation of such species to the considered competitive layer will be another challenge.

– Considering the biota in place, Giraud et al. (2016) considers that 2% of the deep-water input in the considered area is enough to modify the phytoplankton assemblage. After 6 days of incubation in a bottle containing partly deep water, population diversity, i.e. abundance and composition, estimated by pigment distribution (Vidussi et al. 2001) of phytoplankton were modified compared to standards, notably for cyanobacteria, which were depleted. The effect was significant with up to 2% of the deep-water input, as for pigment concentrations. This result could be interpreted as a significant effect of OTEC effluent on the picophytoplankton in the −150-m deep area in blue in Figs. 10 and 11, corresponding to 2% of the difference with the standard condition. But the deep water, with a 10-fold higher content of nitrate and a double concentration of silicate, tends to increase significantly the primary production. However, this last result should make managers aware of the threat of inefficient OTEC deployment: deploying a land-based OTEC plant could induce severe effects considering the lack of dilution and the direct effluent close to or even on the shore. With a floating OTEC platform, the shift on phytoplankton assemblage seems to be limited to the *Prochlorococcus* population. For details, please read Giraud et al. (2016)

Moreover, AKUO ENERGY subcontracted this study to ALYOTECH and CREOCEAN, which provided a study which made it possible to determine the acreage of mixed water proportion in the diffusion layer (Auvray et al. 2012b). This numerical modelling was based on MIKE 3FM HD software for dilution plume extension, on CORMIX software (US EPA) for vertical advection (due to temperature, salinity and volumetric flow rate) and Mercator database. Currentology was performed, based on the planned site 5.3 km off Bellefontaine, working in an area including all the Lesser West Indies archipelagos then, focusing on the OTEC plant position, off Martinique, in six steps, each one being more clearly focused and in greater detail. Considering this surface, the side effects were appropriately and realistically estimated (Auvray et al. 2012b).

In order to understand properly Figs. 10 and 11, it is of utmost importance to note that (1) the authors choose to show the most extended result of simulation using over 13 of the worst conditions for limiting the dilution plume (Auvray et al. 2012b). Auvray et al. (2012b) chose themselves to show their own most extended results from their pool iteration for each condition. Alternative conditions located the plume extending to form an oblong a furlong distant from the plant are illustrated in Fig. 10, but the authors discarded it, considering that the more extended condition was the most informative; (2) in Figs. 10 and 11, the whole effluent was considered and (3) the extent of the dilution area was obtained after many iterated simulations were performed by ALYOTECH and CREOCEAN on behalf of AKUO ENERGY and the most disadvantageous result was chosen, i.e. the most extended dilution plume (Auvray et al. 2012a).

Considering the study performed by Giraud et al. (2016), the significant threshold effect is 2%. Considering the most selective conditions maximizing the temperature difference, the upper and lower temperatures observed were, respectively, 28 °C for subsurface water and 8 °C for effluent mixed water. A threshold effect in the field for 2% was observed at 0.48 °C temperature decrease. In other words, the impact of OTEC on the plankton assemblage could be observed, shown in Figs. 10 and 11, for the turquoise and inner areas. However, authors outline that this evaluation involves conditions which are three times more extreme for the most extended acreage of dilution plume, because of the inclusion of 13 conditions associated with the most extended plume (Auvray et al. 2012a), because CREOCAN and ALYOTECH teams chose the most extended model for each condition and because of the choice of the authors to present the worst temperature condition simulation. Despite the choice of conditions which were three times more extreme, the dilution plume impacting the considered biota would be a 22-km^2 lens of water between −130 and −160 m depth, 4 km distant at least from the shore and the coastal shelf. For all the conditions, please refer to Table 2. Considering the seagoing ships in Martinique, i.e. the exclusively artisanal fisheries which do not exploit such depths, recreational sailing and diving boats, the OTEC artificial upwelling is expected to have no effect on human activities and a limited positive or negative impact on wildlife.

If we consider the other sites where OTEC could be implanted, the intertropical costal/insular belt, seagoing activities would be expected to be similar to those observed in Martinique (artisanal fisheries excluding trawling, pleasure sailing and diving. The conclusion for the Martinique case study regarding the impact of artificial upwelling is that it could be regarded as positive, therefore an incentive for the other places. However, OTEC is a form of exploitation of the deep-sea environment and other places where OTEC could be implanted should be warned of potential degradation of the marine environment because of the lack of knowledge about the marine environment, and particularly the deep sea environment, and the lack of survey facilities made available by France in its overseas territories (Table 3).

(2) Bromoform ($CHBr_3$, CAS number: 75-25-2) is a flame retardant, a solvent and a water treatment by-product in the case of electrochloration which is an antifouling process for producing sodium hypochlorite (NaClO) at 0.4 mg/L. NaClO generates bromoform by its effect on organic matter. The OTEC thermal exchange process involves water circulation in small-diameter pipes which are vulnerable to biofouling and could clog, thus stopping the OTEC operations; antifouling is therefore critical.

In order to prevent this problem, sodium hypochlorite has been chosen to inhibit biota colonization of pipes. NaClO is already used for wastewater treatment (Abarnou 2013) and is a cleaning/disinfecting agent broadly used in the sanitation context.

Tropical conditions involve warm oligotrophic euphotic water. In such condition, sodium hypochlorite is fully converted into bromoform but Sansone and Kearney (1981) indicate that the lack of organic matter in this environment limits the bromoform formation. Moreover, selective non-toxic alternatives exist to limit the use of chemicals such as endocrine traps but they are mainly developed to target one pest. However, such techniques must be supported by prior intense and continuous biological studies. In the case of OTEC, the potential biofoulers are multiple (crustaceans, molluscs…) but they come from a bathyal layer where the fauna and flora are unknown. In other words, a generalist antifouling agent would be necessary.

Bromoform is classified as a slightly toxic chemical by the US National Toxicology Program acute toxicity studies. Bromoform has a slightly toxic effect on rodents via the oral route but has no effect on them in the case of inhalation and intraperitoneal exposure; this is so for rodents and for other mammals tested. Bromoform has a carcinogenic pattern. Considering the aquatic ecotoxicology effects, bromoform induces mortality (LC50 at 96 h) on marine *Penaeus aztecus* (brown shrimps); however for a 26,000 μg/L mean concentration, in flow-through conditions, toxicity is slight (Anderson et al. 1979; Gibson et al. 1981). Accumulation in the same species *P. aztecus* is observed as from 30 μg/L. With regard to fish, Atlantic menhaden (*Brevoortia tyrannus*), sheepshead minnow (*Cyprinodon variegatus*), *Cyprinus carpio* and bluegill *Lepomis macrochirus* were tested.

Like *P. aztecus*, the Atlantic menhaden accumulates bromoform as from 30 μg/L (Gibson et al. 1981) for a LC50 about 12,000 μg/L mean (Anderson et al. 1979). Ward et al. (1981) estimated bromoform as slightly toxic. Non-observable effect concentration (NOEC) was estimated at 15, 000 μg/Lin flow through conditions and 2900 μg/L in static conditions for sheepshead minnows, using growth and hatching as effect criteria—a slightly toxic level was reported. (Ward et al. 1981). Lowest observable effect concentration (LOEC) was reported for 8500 μg/L after 28 days (Ward et al. 1981). In *Cyprinus carpio* eggs, LC50 was reached for 52,000 to 80,000 μg/L, corresponding also to a slightly toxic product (Mattice et al. 1981). For bluegills, Buccafusco et al. (1981) reported a LC50 after 24 h of 33,000 μg/L and, after 96 h, about 29,000 (mean). Bromoform is slightly toxic for bluegills.

Bromoform was tested on *Crassostrea gigas* (Virginia oyster), hard and littleneck clams (*Mercenaria mercenaria* and *Protothaca staminea*). *Crassostrea virginica* thrive up to a concentration of 30 μg/L, but mortality occurs at 40,000 μg/L mean (flow through, after 96 h) (Gibson et al. 1981). Hard clams were less vulnerable: mortality occurs at 140,000 μg/L (Gibson et al. 1981), but littleneck clams presented mortality upon 7000 μg/L. Bromoform is not toxic for molluscs.

Renewable algae, *Selenastrum capricornutum*, and other bacillariophycae were exposed to bromoform by U.S. EPA (1978). Mean EC50 value for the effect on chlorophyll is expected, following the different duration protocols, between 63,600 μg/L after 24 h and 38,600 μg/L after 96 h. Minimal EC50 concentration was 26,100 μg/L, and NOEC (for chlorophyll content) after a 96-h experiment is 10,000 μg/L. Photosynthesis is the most vulnerable pathway with an EC50 mean value of about 12,300 μg/L after 96 h; *Skeletonema costatus* is more vulnerable than *S. capricornutim* (U.S. EPA 1978), leading to population changes. Erickson and Hawkins (1980) report a physiological effect on bacillariophycae after 48 h for an average concentration of 2000 μg/L.

For zooplankton, brine shrimp nauplii (*Artemia salina*) show teratogenous development between 250 and 25,000 μg/L after 24 h, a concentration close to that of the Opossum shrimp's LC50 (*Americamysis bahia*) (US EPA, 19 μg/L78). For water fleas (*Daphnia magna*), mortality is reported at much earlier stages (<24 h) with a 56,000 μg/L LC50 value after 24 h in static conditions (LeBlanc 1980). LC50 value after 48 h is about 46,000 μg/L for a NOEC close to 7800 μg/L. *Daphnia pulex* is more vulnerable to bromoform, with a (renewed) LC50 mean value after 96 h of about 44,000 μg/L after 12 h (Trabalka and Burch 1978).

Data exist too for amphibians, but there are no amphibians in the Caribbean Sea where OTEC installations will be implanted.

At worst, bromoform is slightly toxic for marine animals and we will be extremely unlikely to exceed the NOEC limit, regarding the marine dilution promoted by the intense flow from the OTEC plant (100,000-m square/h of water). In order to prevent biofouler damage, bromoform wastewater is already commonly used in industrial processes. For example, drinking water is treated continuously with an annual rate per consumer between 0.27 and 0.82 kg of bromoform for its disinfection. The antifouling effect of bromoform is reached with a 1 mg/L during fugacious pikes for 40 m^3 s^{-1} per 1000 MW produced. In other words, the concentration of fugacious pike will not reach the lowest NOEC (7800 μg/L, for *Daphnia magna*) even the lowest effect or LOEC observed (2000 μg/L for bacillariophycae) before the intense dilution described previously. Figures 10 and 11 illustrate this dilution and show how bromoform will be located spatially, but it does not show the fugacity of the treatment. The three-dimensional model developed for simulating OTEC effluent dilution allows for the selection of better conditions to promote dilution too, and seasonal events like the presence of humpback whales are well known enough to be able to select a correct treatment period. Moreover, regarding the need for organic matter for bromoform formation, Sansone and Kearney (1981) consider NaClO conversion as more than 100-fold slower than in temperate coastal waters. In other words, the time during which dilution will occur will be at least be 100-fold longer.

For a speed marine stream (about 0.5 m s^{-1}), the dilution is severely enhanced and the plume could reach a furlong at maximal extension before being undetectable.

Sound impact should not be underestimated, because the OTEC floating plant is expected to produce a permanent noise. Dolphins are located close to Bellefontaine because of the low level of disturbance of this area (this part of the Caribbean Sea is partially protected from the wind by the Pitons du Carbet and frequentation by boats is relatively low). However, the OTEC plant could produce enough noise to induce the movement of resident dolphins to go elsewhere perhaps in close proximity to other islands which could consequently lead to obstruction to whale watching operations. Moreover, it could be a stress on the local wildlife; so, the sound impact was therefore investigated.

During the construction phase of the project, the noise has been calculated as higher than the standard noise of the ocean, especially at the 900 m depth considering the submarine works of anchorage and of cable laying and embedding.

During the operative stage, the noise is expected to reach 45–89 Hz frequency range. The noise is under the hazardous level of 100 to 2000 Hz for marine fauna (Ducatel et al. 2013) and only in the immediate vicinity of the OTEC plant. However, this is the first implementation of an operational OTEC installation, so this evaluation is only based on simulations and should be improved in the field.

Conclusion

OTEC is expected to be one of the renewable energy solutions, completing the mix of intermittent renewable energies (wind, sun or tide dependent), by a base load supply thanks to the mixing in a Rankine heat exchanger of cold bathyal water and warm surface water. OTEC technology calls for the installation of an anchored a floating structure, connected to bathyal zone with a suction pipe and to the landing site with a high voltage cable.

Providing power in the Caribbean context reduces the petroleum dependence for power plants, a strategic and economic asset, despite the limited labour involved. However, OTEC technology would be implemented at the risk of altering the marine environment because effluents could impact marine biodiversity hotspots. Extreme climatic conditions would have to be forecast, and electromagnetic and sound pollution would have to be monitored. Furthermore, the population safety is involved because of the huge coolant volume, and the impact on fisheries is yet to be defined. The bathypelagic input is expected to be nutrient rich but not less oxygenized than the −150-m deep sea layer where the effluent will be located. The maximal extend of the area significantly affected in its primary production, and plankton composition will reach 22 km^2 but located at a depth of 150 m. The expense of such an impact study would be considerable since the exposed biocoenosis has been insufficiently studied to date, but OTEC is frequently designed for tropical areas. Environmental awareness is often lacking locally, but OTEC installations should be set up with the informed consent of the population, regarding its cost, its potential impact, its controversial presence and its renewable status. For the Martinique case study, the expected impact modelization and population consultation at local scale, in the neighbourhood of the landing site near Bellefontaine, will be reported.

OTEC technology needs consistent column water stratification with thermic contrast close to islands. Considering the Martinique case study, the floating OTEC system seems to be a safer project than land-based one. However, studies must to be confirmed by real condition monitoring. Finally, OTEC could be an outstanding opportunity for deep ocean exploration.

The present publication illustrates that OTEC could not be implemented without an efficient prior/preliminary field study. The first OTEC plant in the world in Martinique calls for the assistance of many specialists, in the fields of oceanography, taxonomy, effect of deficiency removal, toxicology, etc. without taking into account the OTEC construction and engineering effort. OTEC implementation in Martinique benefits from decades of studies on this coastal area which, despite their shortcomings, were a more consistent database than for most of the other similar tropical island which do not attain the same HDI level. In the same way, local specialists helped for biota inventories. A key point for the suitability of OTEC diffusion will be its scientific support for territories where local support is lacking: the difficulties that OTEC faced in Martinique will probably be faced in the other insular territories which are prospective OTEC sites. Considering the global warming challenge, the vulnerability of the tropical islands and the international collaboration and solidarity reached for critical issues, international organizations could rightly promote the creation of a scientific task force composed of experienced scientists having already contributed to overcoming difficulties involved in OTEC implementation and able to help, even develop the local scientific community in order to ensure the success of OTEC, including its optimal social acceptance.

From a practical point of view, a floating OTEC installation is expected to induce a very local seawater modification at about 150 m depth considering the biological tests on plankton performed by Boye et al. (2015) and Giraud et al. (2016). Moreover, the nutrient and oxygen contents of deep seawater in the planned site of the floating OTEC plant are very close to surface conditions. However, the electromagnetic field effect is not known and will have to be monitored once the floating OTEC is operational.

To conclude, OTEC could be considered as an opportunity for renewable energy and the real scale reached in Martinique will make it possible to test the impact of OTEC on the marine environment. OTEC is still very expensive, because France used its European Union grant from NER 300 to pay 300,000,000 € to build it. OTEC promoters, all over the world, expect that this cost will decline in order to enhance the economic accessibility of OTEC technology for tropical islands and coastal areas. Nevertheless, the price to pay should include the environmental impact and the cost of scientific research to improve the knowledge about the local marine environments. Considering the global warming emergency, (1) the two centuries between the OTEC invention by Carnot (1824) and the OTEC implementation, (2) the continuous ambition to translate OTEC technology to reality has led France to call for the release of funds from the EU and (3) make the effort to ensure a suitable OTEC implementation. However, if the OTEC implementation in Martinique fails, the OTEC opportunity is unlikely to present itself again.

Acknowledgements Authors want to thank DCNS and CTM for allowing them to use classified documents in order to write this paper. The authors sincerely thank Constance Haig for the first revision of the text and Stella Ghouti for her quick, extensive and efficient English reviewing.

References

Abarnou A (2013) Contamination chimique du milieu marin : de la mesure à l'évaluation des risques. Ph.D Thesis Brest. 128pp

Anderson DR, Bean RM, Gibson CI (1979) Biocide by-products in aquatic environments. Quarterly Progress Report

AREC (2012a) http://atlas-caraibe.certic.unicaen.fr/fr/page-30.html ***In French***. Accessed April 30 2016

AREC (2012b) http://atlas-caraibe.certic.unicaen.fr/fr/page-28.html ***In French***. Accessed April 30 2016

Autorité Environnementale (2015) Avis de l'Autorité Environnementale sur le dossier de demande d'autorisation d'exploiter une installation classée pour la protection de l'environnement (ICPE). 9pp. http://www.martinique.developpement-durable.gouv.fr/IMG/pdf/AvisAE_AKUO-NEMO_Bellefont_140815vs_cle2b42d9.pdf Accessed 9 July 2016

Auvray C, Bouchet T, Blouin V (2012a) Etudes météocéaniques et du rejet: modélisation des courants. Energie Thermique des Mers (ETM) Projet de centrale pilote en Martinique. 12/INC/191. 35pp. ***In French. Confidential***

Auvray C, Bouchet T, Blouin V (2012b) Etudes météocéaniques et du rejet : modélisation des rejets. Energie Thermique des Mers (ETM) Projet de centrale pilote en Martinique. 12/INC/191. 65pp. ***In French. Confidential***

Balmori A (2015) Anthropogenic radiofrequency electromagnetic fields as an emerging threat to wildlife orientation. Sci Tot Env 518-519: 58–60

Berger LR, Berger JA (1986) Countermeasures to microbiofouling in simulated ocean thermal energy conversion heat exchangers with surface and deep ocean waters in Hawaii. Appl Environ Microbiol 51(6):1186–1198

Boye M, Giraud M, Garçon V, Lejart M, Auvray C, Bœuf M, De La Broise D. (2015) Ocean thermal energy conversion, the potential impact on microplankton of bottom water discharge at sub-surface. Association for the Sciences of Limnology & Oceanography, 22–27 February 2015 Granada

Brandt AR (2011) Oil depletion and the energy efficiency of oil production: the case of California. Sustain 3(10):1833–1854

Buccafusco RJ, Ells SJ, LeBlanc GA (1981) Acute toxicity of priority pollutants to bluegill (*Lepomis macrochirus*). Bull Environ Contam Toxicol 26(4):446–452

Carnot S (1824) Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance. Bachelier Ed, Paris. 59pp. *In French*

Clark CE, Burnham AJ, Harto CB, Horner RM (2012) Introduction: the technology and policy of hydraulic fracturing and potential environmental impacts of shale gas development. Environ Pract 14(4):249–261

David V, Sautour B, Chardy P (2007) Successful colonization of the calanoid copepod *Acartia tonsa* in the oligo-mesohaline area of the Gironde estuary (SW France)—natural or anthropogenic forcing? Est, Coast Sh Sci 71(3–4):429–442

DEAL Martinique, Région Martinique (2013) Schéma Régional Climat Air Energie Martinique, 114pp. http://energie.mq/wp-content/uploads/2013/07/18-04-2013-SRCAE-Martinique_Etat-des-lieux.pdf

Dengler AT Jr, Wilde P (1987) Turbidity currents on steep slopes: application of an avalanche-type numeric model for ocean thermal energy conversion design. Ocean Engin 14(5):409–433

Ducatel C, Audoly C, Auvray C (2013) Prediction of OTEC underwater radiated noise and assessment of noise disturbance on cetaceans. 1st Underwater Acoustics international conference and exhibition. Corfu, June 2013

Dugger GL (1975) Ocean thermal energy conversion. Astron Aeron 13(11):58–63

Erickson SJ, Hawkins CE (1980) Effects of halogenated organic compounds on photosynthesis in estuarine phytoplankton. Bull Environ Contam Toxicol 24(6):910–915

Faizal M, Ahmed MR (2013) Experimental studies on a closed cycle demonstration OTEC plant working on small temperature difference. Renew Energy 51:234–240

Gaela HR, Ferry R (2015) Notes on some hydroids (Cnidaria) from Martinique, with descriptions of five new species Revue suisse de zoologie; annales de la Société zoologique suisse et du Muséum d'histoire naturelle de Genève 122, 2, 213–246

Galenon P (2011) Les énergies renouvelables Outre-mer: laboratoire pour notre avenir, Conseil économique, social et environnemental Ed, Paris, 115pp. http://www.collectivites-locales.gouv.fr/files/files/2011_07_rapportenergies_renouvelables.pdf In French. Accessed 13 July 2016

Gibson CI, Tone FC, Wilkinson P, Blaylock JW, Schirmer RE (1981) Toxicity, bioaccumulation and depuration of bromoform in five marine species. Pacific Northwest Lab, Richland

Giraud M, Boye M, Garçon V, Donval A, de la Broise D (2016) Simulation of an artificial upwelling using immersed *in situ* phytoplankton microcosms. J Experimental Mar Biol Ecol 475:80–88

Goulet TL (2006) Most corals may not change their symbionts. Mar Ecol Prog Series 321:1–7

Hammond GP, Howard HR, Jones CI (2013) The energy and environmental implications of UK more electric transition pathways: a whole systems perspective. En Pol 52:103–116

Harrison JT (1987) The 40 MWe OTEC plant at Kahe Point, Oahu, Hawaii: a case study of potential biological impacts. NOAA Technical Memorandum NMFS NOAA-TM-NMFS-SWFC-68

Haslett SK (2009) Coastal systems, Routledge, 2009. 240pp. 107pp

Havens P, Morgan C, MacDonald DA (2010) Environmental planning and management for OTEC pilot projects. MTS/IEEE Seattle, OCEANS 2010, art. no. 5664049

Höffle H, Wernberg T, Thomsen MS, Holmer M (2012) Drift algae, an invasive snail and elevated temperature reduce ecological performance of a warm-temperate seagrass, through additive effects. Mar Ecol Prog Ser 450:67–80

Howarth RW, Santoro R, Ingraffea A (2011) Methane and the greenhouse-gas footprint of natural gas from shale formations. Clim Ch 106(4):679–690

IEDOM (2015a) Martinique rapport annuel 2015. 180 p. In French. Accessed 5 July 2016 http://www.iedom.fr/martinique/publications/rapports-annuels-117/

IEDOM (2015b) Saint Barthélémy rapport annuel 2015, 96 p. Accessed 5 July 2016 http://www.iedom.fr/IMG/pdf/ra2015_saint-barthe_lemy.pdf

Ikegami Y, Uehara H (1994) Optimum design point for a closed-cycle OTEC system. Proceedings of the International Offshore and Polar Engineering Conference 1, 383–389

INSEE (2015) Enquête budget de famille 2011, INSEE Analyses Martinique n°7. In French. Accessed 5 July 2016, https://www.insee.fr/fr/statistiques/1288246.

Jiai Y, Nihous GC, Richards KJ (2012) Effects of ocean thermal energy conversion systems on near and far field seawater properties—a case study for Hawaii. Journal of Renewable and Sustain En 4 (6), art. n°063104

Jones I, Leach H (1999) Isopycnic modeling of the North Atlantic heat budget. J Geoph Res: Oceans 104(C1):1377–1392

Joubert WR, Thomalla SJ, Waldron HN, Lucas MI, Boye M, Le Moigne FAC, Planchon F, Speich S (2011) Nitrogen uptake by phytoplankton in the Atlantic sector of the Southern Ocean during late austral summer. Biogeosciences 8(10):2947–2959

Journal Officiel (2012) Décret no 2014-285 du 3 mars 2014 modifiant la nomenclature des installations classées pour la protection de l'environnement. 18pp. ***In French***. Accessed April 30 2016. https://www.legifrance.gouv.fr/jo_pdf.do?id=JORFTEXT000028680960

Kim NJ, Ng KC, Chun W (2009) Using the condenser effluent from a nuclear power plant for Ocean Thermal Energy Conversion (OTEC). International Communications in Heat and Mass Transfer 36(10):1008–1013

Krause JW, Nelson DM, Brzezinski MA (2011) Biogenic silica production and the diatom contribution to primary production and nitrate uptake in the eastern equatorial Pacific Ocean. Deep-Sea Research Part II: Topical Studies in Oceanography 58(3–4):434–448

Krylov VV (2010) Effects of electromagnetic fields on parthenogenic eggs of *Daphnia magna* Straus. Ecotoxicol Environ Saf 73(1):62–66

LeBlanc GA (1980) Acute toxicity of priority pollutants to water flea (*Daphnia magna*). Bull. Environ Contam Toxicol 24(5):684–691

Lee W, Yang K-L (2014) Using medaka embryos as a model system to study biological effects of the electromagnetic fields on development and behavior. Ecotoxicol Environ Saf 108:187–194

Mattice JS, Tsai SC, Burch MB, Beauchamp JJ (1981) Toxicity of trihalomethanes to common carp embryos. Trans Am Fish Soc 110(2):261–269

Menesguen A, Monbet Y, Cousin F (1989) OTEC's subsurface discharges of deep ocean water: modelling their effects on the primary production. American Society of Civil Engineers. Ocean Energy Recovery conference proceeding. 235–246

Morisaki T, Ikegami Y (2012) Research on ocean thermal energy conversion using HFC245fa as working fluid. Proceedings of the International Offshore and Polar Engineering Conference, pp. 776–782

Nihous GC (2005) An order-of-magnitude estimate of ocean thermal energy conversion resources. Journal of Energy Resources Technology, Transactions of the ASME 127(4):328–333

Nihous GC (2007) An estimate of Atlantic Ocean thermal energy conversion (OTEC) resources. Ocean Engin 34(17–18):2210–2221

NRJRUPplus (2007) Modelling study for the exploitation of marine resources for electricity generation in the outermost regions. Dirección General de Asuntos Económicos con la Unión Europea—Gobierno de Canarias (Ed). 68pp

OMEGA (2015) Bilan Energétique de la Martinique, OMEGA Eds, Ducos, 68pp. In French. http://energie.mq/wpcontent/uploads/2016/12/OMEGA_Bilan_energetique_Detaille_2015.pdf

Panwar NL, Kaushik SC, Kothari S (2011) Role of renewable energy sources in environmental protection: a review. Renew Sustain En Rev 15(3):1513–1524

Plocek TJ, Laboy M, Marti JA (2009) Ocean-thermal-energy conversion. JPT, J Petrol Technol 61(7):65–66

Rajagopalan H, Nihous GC (2013) An assessment of global ocean thermal energy conversion resources with a high-resolution ocean general circulation model. Trans ASME 135:1–9

Rao G, Lin A (2011) Distribution of inundation by the great tsunami of the 2011 Mw 9.0 earthquake off the pacific coast of Tohoku (Japan), as revealed by ALOS imagery data. Intern J Rem Sens 32(22):7073–7086

Rio Carrillo AM, Frei C (2009) Water: a key resource in energy production. En Pol 37(11):4303–4312

Sansone FJ, Kearney TJ (1981) Chlorination kinetics of surface and deep tropical seawater. In R.L. Jolley, H.Gorchev, and D.R.Hamilton,Jr. (Eds.), Water chlorination: environmental impact and health effects, 5, 59, 755–762

Secroun J-P (2016) NEMO Inquisitory OTEC. E1500014/97 172 pp

Semmari H, Stitou D, Mauran S (2012) A novel Carnot-based cycle for ocean thermal energy conversion. Energy 43(1):361–375

Tortell PD, Maldonado MT, Granger J, Price NM (1999) Marine bacteria and biogeochemical cycling of iron in the oceans. FEMS Microbiol Ecol 29(1):1–11

Trabalka JR, MB Burch (1978) Investigation of the effects of halogenated organic compounds produced in cooling systems and process effluents on aquatic organisms. In R.L. Jolley, H. Gorchev, and D.R. Hamilton, Jr. (Eds.), Water chlorination: environmental impact and health effects: 163–173

U.S. Environmental Protection Agency: U.S. EPA (1978) In-depth studies on health and environmental impacts of selected water pollutants, U.S. Environmental Protection Agency, Duluth, Minnesota

Uehara H, Ikegami Y (1993) Parametric performance analysis of OTEC using Kalina cycle. Solar Engin:203–207

Vega LA (1992) Economics of ocean thermal energy conversion (OTEC). In: R.J. Seymour, ASCE Publications. Ocean energy recovery—the state of the art, pp. 152–181

Vega LA (2010) Economics of ocean thermal energy conversion (OTEC): an update. Offshore technology conference. Houston, Texas, USA, 3–6 May 2010

Vega LA (2012) Ocean thermal energy conversion. Encycl Sustainab Sci Technol, 7296–7328

Vidussi F, Claustre H, Manca BB, Luchetta A, Marty JC (2001) Phytoplankton pigment distribution in relation to upper thermocline circulation in the eastern Mediterranean Sea during winter. J Geophys Res 106:19939–19956

Ward GS, Parrish PR, Rigby RA (1981) Early life stage toxicity tests with a saltwater fish: effects of eight chemicals on survival, growth, and development of sheepshead minnows. J Toxicol Environ Health 8(1–2):225–240

Werner E (1981) Integrated OTEC-mariculture system. Proceedings of the Ocean Energy Conference 1, pp. 229–233

Worrall P, Hurtt J (2010) Dynamic medium voltage power cables. Proceedings of the Annual Offshore Technology Conference 3, pp. 2220–2234

Yoza BA, Nihous GC, Takahashi PK, Golmen LG, War JC, Otsuka K, Ouchi K, Masutani SM (2010) Deep ocean water resources in the 21st century. Mar Technol Soc J 44(3):80