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Levelized Cost of Energy: a first evaluation for a self balancing kinetic turbine

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Abstract

Since 2009, the team DIMEG Unical and SintEnergy srl have been developing an innovative kinetic turbine able to produce energy form tidal currents. The machine is able to maintain the frontal position to the flow only thanks to its geometry and technical solutions. This turbine doesn't need any concrete structure, nor pylons or floating devices; in terms of energy conversion, it doesn't use any nacelle, gearbox, external generator, but only a little stabilizer, a permanent magnetic generator and a coast anchoring system able to retain the machine during the working operations. A first cost evaluation has been performed in this work, together with an approximate LCOE calculation, in order to compare this device to the other ones in the pre commercialization phase. The project is in an early stage of the development, but quite ready for a prototype realization.

Keywords: LCOE; tidal turbine; cost of energy; self balancing, Unical SintEnergy

1. Introduction

The population of the world is growing up and the energy demand is growing too due to the people and industries needs. Data from several sources [1] show that the primary world energy consumption consists of 35.6% on oil (3952.8 million tons of oil equivalent, Mtoe), 23.8% on natural gas (2637.7 Mtoe), 28.6% on coal (3177.5 Mtoe), 5.6% on nuclear power (622 Mtoe) and 6.4% on hydroelectricity (709.2 Mtoe).

One of the main climate change causes is the increase in greenhouse gas emissions in the atmosphere, which includes carbon dioxide (CO_2) mainly caused from the process of transformation (combustion) of the fossil fuels, but also dangerous for the health.

Renewable energies, including biomass, solar and wind power, marine energy, are the natural resources which can be retrieved in a measurable time period and are more environmental friendly compared to the non-renewable ones.

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In this context, among the renewable ones, the exploitation of the ocean energy for electricity generation has to be considered, focusing on tidal currents and waves, suitable for converting the kinetic energy in electricity using different methods and technologies.

2. State of the art

2.1. Main working principles

The tidal power exploitation can be performed in several ways, depending on technologies. By arranging a barrage or lagoon, usually using a bank or offshore impoundment, the incoming and outgoing tides can be blocked and then create a head of water. A different approach is to install underwater turbines in locations where high tidal currents can be found. These machines convert the kinetic energy of the tidal stream to power turbines, in a similar manner in which windmills extract energy from the wind. However there are several differences in the operating conditions: i.e. water density is 800 times greater than the air one and the water flow speed is much lower. Tidal current turbines have to be able to generate during both flood and ebb tides and also withstand the structural loads when not generating electricity.

2.2. Common applications

The simplest form of a tidal current turbine consists [2] of a number of blades mounted on a hub or rotor (horizontal or vertical axis), a gearbox, and a generator (Fig. 1). The hydrodynamic effect of the flowing water, pasting the blades, causes the rotor to rotate, thus turning the generator connected via a gearbox to the rotor, able to convert the rotational speed of the rotor shaft to the desired output speed of the generator shaft. The electricity generated is transmitted to land through cables. These three parts are mounted to a support structure, required to withstand the harsh environmental loadings.

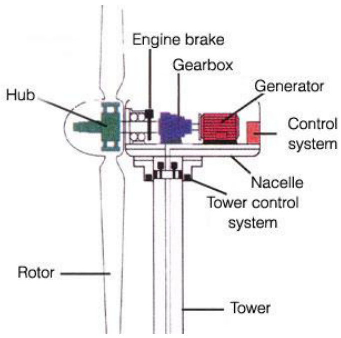


Fig. 1 Typical tidal turbine breakdown

Basically there are three main support structure options [2] for the installation of a tidal current turbine. The first is known as a gravity structure and consists of a large mass of concrete and steel attached to the base of the structure to achieve stability. The second option is known as a piled (similar to a wind tower) structure which is pinned to the seafloor using one or more steel or concrete beams. The last one is such as a floating structure, usually moored to the seafloor using chains or wire. The turbine, in this case, is fixed to a downward pointing vertical beam, which is fixed to the floating structure.

2.3. State of the art: development

In order to define the development state of a project there are several steps that developers must progress through on the journey between initial concept and commercial product [3], also known as the Technology Readiness Level as in Table 1.

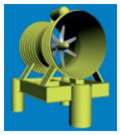
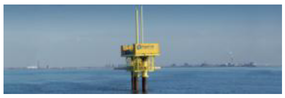
Table 1 Technology Readiness Level

TRL	Description	Indicative Ocean Energy Device
1	Basic principles observed and reported	**Discovery/Concept Definition;** Scientific research begins to be translated into applied research and development where basic principles are observed and reported. Technology concept and application are formulated and investigated through analytic studies and in-depth investigations of principal design considerations. This stage is characterized by paper studies, concept exploration, and planning. **Scale Guide 1:25 – 1:100 (Small Scale)**
2	Technology concept and/or application formulated	
3	Analytical and experimental critical function and/or characteristic proof of concept	**Early Stage Development, Design and Engineering;** Active research is initiated, including engineering studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. **Scale Guide 1:25 – 1:100 (Small Scale)**
4	Component and/or partial system validation in a laboratory environment	**Proof of Concept;** Early stage proof-of-concept system or component development, testing and concept validation. Critical technology elements are developed and tested in a laboratory environment, and computer simulation of the device will be carried out. **Scale Guide 1:10 – 1:25 (Medium Scale)**
5	Component and/or partial system validation in a relevant environment	**Technology Laboratory Demonstration;** Basic technological components are fabricated at a scale relevant to full scale and integrated to establish and verify subsystem and system level functionality and preparation for testing in a simulated environment. Subsystem level interfacing testing demonstrated at model scale. **Scale Guide: 1:2 – 1:5 (Large Scale)**
6	System/subsystem model validation in a relevant environment	**System Integration and System Technology Laboratory Demonstration;** System level interfacing/integration testing demonstrated at model or prototype scale. At this level, representative model or prototype system at a scale relevant to full scale, which is beyond that of TRL 5, is tested in a relevant environment, such as a test facility capable of producing simulated waves/currents and other operational conditions, while monitoring device response and performance. Furthermore, the devices foundation concept shall be incorporated and demonstrated. This stage represents a major step up in a technology's demonstrated readiness and risk mitigation and is the stage leading to open water testing. **Scale Guide: 1:2 – 1:5 (Large Scale)**
7	System prototype demonstration in an operational environment	**Open Water System Testing and Demonstration;** Testing may be initially performed in water at a relatively benign location, with the expectation that testing then be performed in a fully exposed, open water environment, where representative operating environments can be experienced. The final foundation/ mooring design shall be incorporated into testing at this stage. **Scale Guide: 1:1 – 1:3 (Large Scale)**
8	Actual system completed and service qualified through test and demonstration	**Open Water System Operation;** The prototype in its final form (at or near full scale) is to be tested, and qualified in an open water environment under all expected operating conditions to demonstrate readiness for commercial deployment in a demonstration project. Testing should include extreme conditions. Production of GWh scale electricity, operating continuously for at least one year. **Scale Guide: 1:1 – 1:2 (Pre Commercial Demonstrator)**
9	Actual system proven through successful mission operation	**Commercial Scale Production / Operation;** Final commercial unit, economic deployment when the technology is ready for mass production and has proven to operate as designed for several years. Array scale projects. **Scale Guide: 1:1 (Full Scale1)**

The modern ocean energy industry is currently leaving the prototype stage for installing the first commercial devices. The first of these [4] came into operation with the Pelamis project (in Portugal) and SeaGen (in Northern Ireland) having completed installation at the end of the 2008.

The following Table 2 summarizes and update (where possible) the state of the art of several technologies coming from [2].

Table 2 Tidal/current technology state of the art

Company	Device (s)	Features	Status	
Atlantis Resource Corporation PTE Ltd. (Singapore) [5]	AR1000 turbine	1MW horizontal axis turbine designed for open ocean deployment. It features a single rotor set with highly efficient fixed pitch blades.	Tested at EMEC in 2011	
Lunar Energy Ltd. (UK) [6]	Lunar Energy Tidal Turbine	Horizontal axis of rotation, hydraulic motor and generator	The device is currently at the design stage of 2.4 MW	
Marine Current Turbines Ltd. (UK) [7]	SeaGen	Twin horizontal axis rotors, two variable-pitch blades (20 m diameter)	Testing in testing system in Strangford Lough (UK), 2 MW of power	
Ocean Flow Energy Ltd. (UK) [8]	Evopod Tidal Turbine	Horizontal axis of rotation, moored structure five-bladed design (4.5 m diameter)	A 1/4th scale mono-turbine Evopod 35kW that will be connected into the 11kV grid at Southend, South Kintyre, Northern Ireland.	
Open-Hydro Ltd. (Ireland) [9]	Open Centre Turbine	Open centre rotor and stator, horizontal axis of rotation (16 m diameter)	Array of two 16m with a capacity of 2 MW each mounted and connected to the grid at the FORCE facility. Bay of Fundy, Nova Scotia	
Pulse Generation Ltd. (UK) [10]	Pulse Tidal Hydrofoil	Reciprocating device utilizing a hydraulic generator	Tested in 2009 into the River Humber (UK) No further information	
Tidal Energy Ltd. (UK) [11]	DeltaStream Turbine	Horizontal axis of rotation, three-bladed design (15 m diameter)	The device is in the development phase; installation is expected in Ramsey Sound.	
ANDRITZ HYDRO Hammerfest Norway [12]	HS1000	Horizontal Axis Turbine	1MW pre-commercial demonstrator deployed at the EMEC tidal test site in the Orkney Isles.	

Verdant Power Ltd. (USA) [13]	Free Flow Turbine	Horizontal axis of rotation, three-bladed design (5m diameter)	On January 23, 2012, the Federal Energy Regulatory Commission (FERC) issued a pilot commercial license for the installation.	

However, even if a great deal of research and investment has been carried out in Europe, there have also been a number of significant developments in other continents, like, for example, Australia: there are at least three companies involved in the research, development and pre-commercial testing of wave energy devices. These include the Western Australian based company Carnegie Corporation, developers of the CETO [14] wave power converter which had a commercial scale demonstration at Freemantle. A commercial scale plant is in progress with connection to the grid due by 2014. Also in Australia, Oceanlinx re-deployed in February 2009 its pilot plant device at Port Kembla on the New South Wales coast south of Sydney. This oscillating power column technology [15] had been under development since it was first deployed in Port Kembla in 2005, and though one of the prototype units is in progress.

3. SintEnergy Turbine

SintEnergy turbine [16] is an innovative solution, see Fig. 2, for collecting energy from tidal currents.

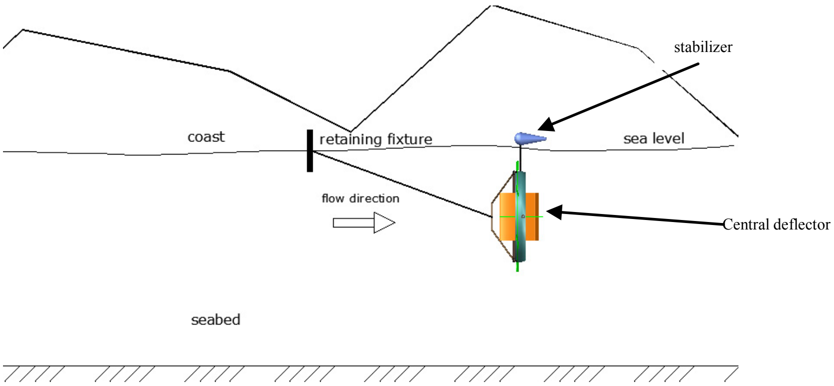


Fig. 2 Working scheme

The machine [17] is based on two contrarotating rotors, a stator, where rotors turn with the built in generator (permanent magnets) producing energy, a central deflector making the machine always aligned to the flow and a vertical stabilizer (a sort of buoy) for maintaining the machine at right depth [18].

The working principle [19] is quite similar to a kite [20]: the machine is in equilibrium in the water (see figs. 2,3,4) by a simple rope (3) subject to a tensile stress, in the right position which doesn't change during the work. The rope is driven by a rigid rod (2) hinged to the coast (see figs. 2, 3).

The weight (W) – reduced by the Archimedes' thrust (T_A) – and the rate of change of the axial momentum (T), the forces which sink or aground the machine, are balanced by the lift produced by the tidal current on the central deflector installed in the middle of the blade discs. This last force (L_r – see Fig. 2) pushes off the turbine, but the combined action of the forces W, T_A, T and R (Fig. 3) makes the turbine able to be in equilibrium in a position, related to the coast, which doesn't change when the tidal velocity changes. This position depends only on the turbine geometrical configuration.

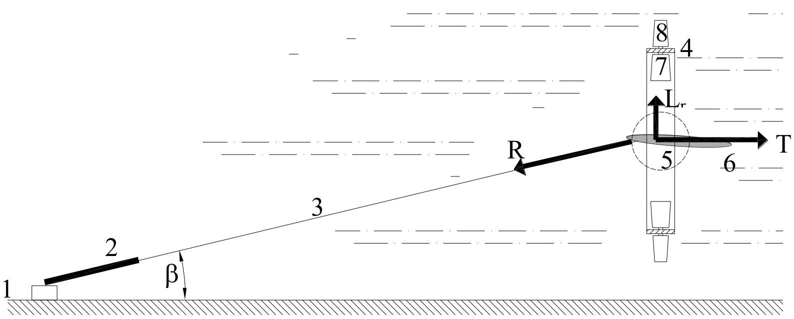


Fig. 3 Machine top view

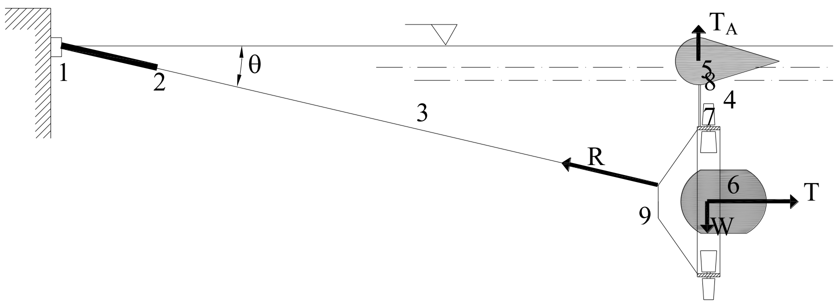
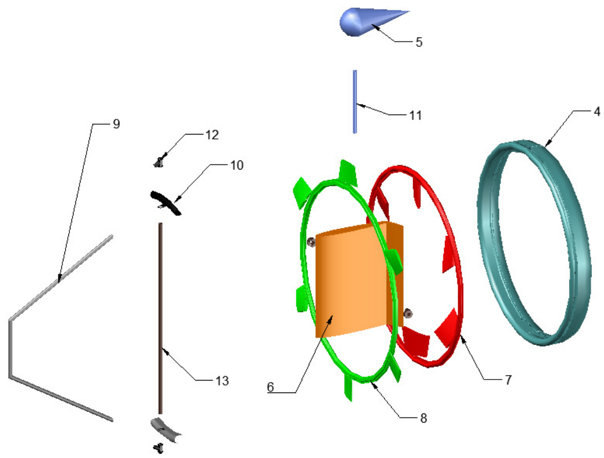


Fig. 4 Front view

	Key				
1	hinge	4	stator	7	internal rotor
2	rod	5	stabilizer	8	external rotor
3	rope	6	deflector	9	rigid frame

	Simbols				
L_r	lift	R*	horizontal resultant	R	resultant
T	drag	T_A	Archimedes' thrust	W	weight
β	attack angle	θ	sinking angle		

Fig. 5 shows the turbine breakdown with two rotors, each of them equipped with 6 blades. The blades of each rotor are connected by circular rings sliding through the stator (4): the two rotors – the external (8) and the internal (7) one – rotate in opposite direction so that they produce equal and opposite torques.



	Legenda				
4	Stator	5	Stabilizer	6	Deflector
7	Internal rotor	8	External rotor	9	Forcella
10	Yoke Support	11	Stabilizer support	12	Yoke support connector
13	Deflector support				

Fig. 5 Turbine breakdown

The vertical deflector (6) is installed in the middle of the blade discs: when the current laps it, the lift force produced (L_r) begins to drag off the turbine. This last force, together with the other ones (T, T_A and W), produces a resultant R (Fig. 3) stretching the rope (3) connected to the machine. The connection rope-turbine is done by a rigid frame (9). In order to maintain the machine in vertical position, to tighten the rope and balance any possible unbalanced stresses, a floating level stabilizer (5), with an aerodynamic shape, has been introduced.

Thanks to this solution no structures, supports or foundations in water, are needed for maintaining the machine in equilibrium, just a simple rope, driven by a rigid rod hinged to the coast.

4. The cost analysis approach

4.1. Energy cost parameter

The expected energy cost is one of the important factors for building such a machine or a farm. In order to define a standard parameter, involving all the variables in the calculations, the "Levelized cost of energy (LCOE)" has been introduced: LCOE is a metric used to evaluate the cost of electricity generation and can be used to compare costs of all types of electricity. Different methodologies have been developed to calculate LCOE; the one used for this analysis is fully described in [21]. In other words, the LCOE is the price at which electricity must be generated from a specific source to break even over the lifetime of the project and is very useful for calculating the costs of generation from different sources.

The main components of LCOE can be split in AEP (Annual Energy Production), Capital Expenditure CAPEX (Capital Expenditure) and OPEX (Operation and Maintenance Costs)

APEX involves site resources, like current velocity and site bathymetry, device geometry, like main dimensions (blade area), specific technology (i.e. horizontal or vertical axis), performances, directly related to the previous variables, availability of the site (permissions, taxes, other costs).

CAPEX are related to device, like foundations, connections to the public or private network, installations (building, transportations): it is important to consider the challenges associated with transportation and installation. Delivery of tidal current turbines from factory to sites requires costly transportation. Some more, there is restriction on the size of objects that can be transported on the road. The installation of tidal current turbines is also very difficult as the size is big and it involves underwater installation. These works will become more challenging and costly when it comes to the transportation and installation of tidal current turbine array.

OPEX are maintenance operation, insurance, lease and transmission charges.

4.2. Case study

To perform a LCOE calculation the first step is to fix the factors affecting the Capital Costs of equipment. The output parameter will be the Cost Of Energy produced: it will depend on the amount of electricity generated and so the yield of the device at that particular location can be a further key input to calculate the cost of energy (in this case already considered for Punta Pezzo site, Messina Strait, Reggio Calabria Italy). The case study involves a machine as follow (see Table 3):

Table 3 SintEnergy turbine case study data

Parameter	Value
External diameter	12 m
Peak power	445 kW
Energy output per unit area rotor	5710 kWh/m^2
Energy production	474748 kWh/year

Usually the main capital costs, in share of the whole standard plant, can be defined starting from [22], as shown in Fig. 6:

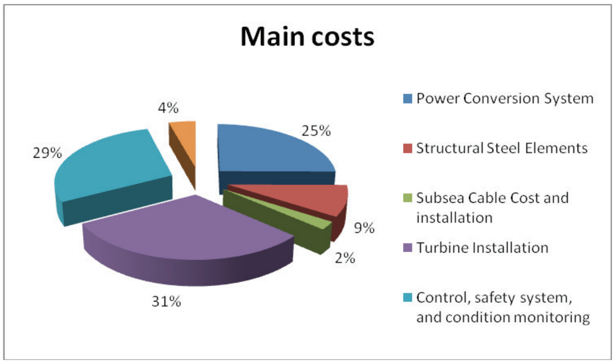


Fig. 6 Tidal machine/plant costs

For the case study, with the breakdown costs detail [23], it is possible to define the breakdown of the installation as shown on Table 4 and Fig. 7

Table 4 SintEnergy turbine breakdown and costs

Costs breakdown	Estimated costs [k€]

Stator and rotors	82.6
Blades	70.5
Generator	60.0
Stabilizer and central deflector	75.0
Main rod, hinge, hoist, etc.	50.0
Electrical connections	25.1
Collector substation	10.3
Transmission line and interconnection	13.9
Electrical material and installation	66.6
Control, safety system, and monitoring	13.0
Access road and site improvement	16.6
Turbine transportation	31.2
Project management	20.8
Total Installed Cost	535.5

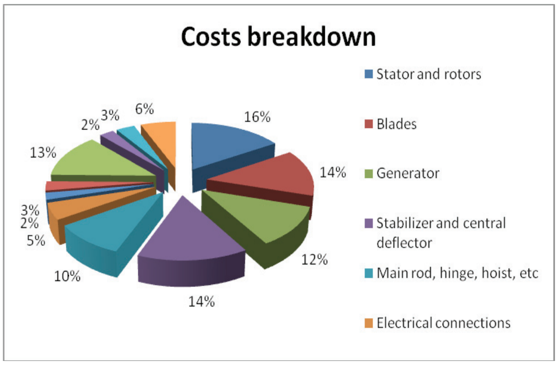


Fig. 7 Costs breakdown share (see Table 4)

Once defined the Total Installed Cost (TIC), assuming an Annual Energy Production (AEP) as in Table 3 at rate of 0.3 €/kWh (government incentives GI), it is possible to calculate a Simply Payback Period (SSP) as:

$$SPP = \frac{TIC}{AEPxGI} = 4.56 \quad years \tag{1}$$

O&M cost can be estimated as 2.5% of the TIC:

$$O\&M = € \ 13387.47 \tag{2}$$

Introducing a Fixed Share Cost (FSC) coefficient due to taxes, debits, and other annual costs, for Italy close to 0.08 [24], the estimated Levelized Cost Of Energy (LCOE) will be:

$$LCOE = \frac{TICxFSC + O\&M}{AEP} = 0.118 \ €/kWh \tag{3}$$

The costs in Table 4 have been evaluated considering the status of the project: at moment, a prototype of 1 m of diameter is in development in terms of feasibility study of generator, the structural and fluid dynamic design, anchoring system, and all above data have been scaled to a 12 m diameter. Considering the development steps fixed as in [3], it is possible to include SintEnergy state of the art at step 5.

5. Some comparisons

The comparison is focused on evaluating, for each source, the LCOE: for tidal turbines there are different technologies or solutions and it is very difficult to perform. Due to several technical variables, for correctly compare the different solutions, the main ones could be: current velocity, site bathymetry, main dimensions (blade area), as consequence the power output (sometimes farms or array solutions are considered). Once the LCOE is evaluated, a wind solution usually is introduced as final benchmark.

In order to compare different machines and installations, it is possible to consider same installed power at different sites (current speeds), produced by a farm or a single machine, or simply compare the plant considering the output power independently from the machine geometry.

Once defined the background, it is possible to write a raw breakdown list of the components, common to different technologies, in order to define a standard for evaluating the costs of each solution and compare the related LCOE. A first comparison is in the Table 5.

Table 5 LCOE comparison for certain plants

	ref.	year	LCOE
MCT SeaGen	[22]	2006	0.146
Kobold	[24]	2005	0.080
Wind land-based	[23]	2011	0.097
Wind offshore	[23]	2011	0.304
SintEnergy	[20]	2014	0.118

The LCOE may vary depending on different markets, government incentives and taxations, for a commercial plant. As in [22] LCOE strongly depends on number of turbines, speed, site availability: more turbines (array) reduce the LCOE, higher speed and availability reduce also the costs and LCOE. Not so many LCOE evaluations for specific plants can be found due to the early step of development (TRL 7-8), in addition only sometimes the evaluation is referred to a single turbine or to a same pick velocity so the costs look like higher. SintEnergy turbine is evaluated at 3m/s of pick speed: 7 m/s velocity increases the AEP and LCOE goes dramatically down.

6. Conclusions

The SintEnergy turbine is designed as "single machine", at a low speed and with less flow energy, but takes its advantages from the low CAPEX costs. No pylons or structural elements or subsea cables, easy installation and maintenance, no gearbox, nacelle and axis control for orientation, built in generator and electronic controls. The higher LCOE, in relation to the other technologies, is mainly due to at the early stage of the development; moreover the SintEnergy turbine is designed as "single machine", is easier to control and could be installed without critical logistic and transportations, due to its modular and compact design.

SintEnergy turbine can increase its energy production maintaining the same geometry, if the installation site change (i.e. North Sea): due to its simplicity, the CAPEX costs don't increase so the LCOE can go down and the machine begins rapidly profitable.

In the last months a new costs evaluation has been performing, so, compared to [20] (step 3 of development), now the CAPEX also have been lowering.

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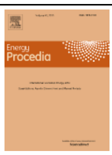

Biography

Giacomo Lo Zupone, graduated in Mechanical Engineering at Politecnico of Bari, since 2004 teacher of Fluid Dinamics and Propulsion Systems at "Euclide" Vocational High School in Bari. Since 2010 member of the SintEnergy Development Team and, from 2012, R&D SintEnergy Technical Director.