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Analytical method towards an optimal energetic and economical wind-energy converter

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ABSTRACT

An innovative concept to convert wind energy in wind-rich ocean regions is presented and analyzed. This concept involves the operation of wind-propelled vessels equipped with hydrokinetic turbines so that the kinetic energy of the water flow relative to the hydrokinetic turbine is converted into electricity. This electric power then is used to split sea water electrolytically into hydrogen and oxygen. A currently missing upper limit of energy conversion of the proposed system is presented, which is based on axiomatic conversion laws. To ensure the requirement of economic profitability the energetic description is widened by an economic description. Normally, the technical analysis precedes the economic assessment of a system. In contrast, a holistic approach is presented which yields the techno-economic optimal design as a trade-off between energetic efficiency and economic profitability. For system optimization Pareto optimization is applied to obtain convergence of the energetic and economic system quantities. The Pareto-frontier, defined as the multitude of all optimal energetic and economical systems, is presented. The application of this analysis shows that typical sailboats with 50 m^2 sail area operating in 10 m/s winds deliver a mechanical power output of about 13 kW and sailing ships with 3200 m^2 produce about 1 MW.

1. Introduction

The transformation of the fossil fuel-based energy supply system into a sustainable system is one of the major societal challenges of the twenty first century. Renewable energy systems need to be developed by meeting the objectives of energetic efficiency, robustness, and affordability. In this paper an analytical optimization of an energy conversion system is demonstrated by considering its energetic and economical aspect. The concept converts wind energy into electric energy using sail-powered vessels. A hydrokinetic turbine is used to convert the relative kinetic water energy into electricity. In a further step the electricity is used to produce hydrogen using sea water. Using electrolysis the electrical energy is converted into transportable and storable chemical energy. The basic concept seems to have been first proposed by Salomon [1] as long ago as 1982, followed by Meller [2], Holder [3], and Gizarra [4], but the first more quantitative analyses have been presented only during the past six years by Platzer [5–7] and Kim [8]. The main advantage of this type of energy supply system is the substitution of air by water for power production. While the vessel is driven by wind power, the hydraulic turbine is driven by the water flow. For the same turbine shaft power the diameter ratio D_l/D_g scales with the square root of the density ratio ϱ_g/ϱ_l where the subscripts g and l indicate "gas" and "liquid"

$$\frac{D_l}{D_g} = \sqrt{\frac{\varrho_g}{\varrho_l}} \approx 3.5\%. \tag{1}$$

Equation (1) shows that the diameter of a hydrokinetic turbine exposed to the same flow speeds is only 3.5% that of a wind turbine to deliver the same amount of power with the water density $\varrho_l = 1000$ kg/m^3 and the air density $\varrho_g = 1.2$ kg/m^3. The reduced hydrokinetic turbine size therefore reduces the investment costs, which scale with the component size. The electric energy produced by the turbine electricity needs to be stored using an adequate energy storage technology, like the conversion into chemical energy. It is reasonable to use the electricity to convert sea water into hydrogen and oxygen using commercially available electrolysers. The hydrogen is than stored in tanks in the hull of the vessel. In the

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present paper a standard sailing ship configuration is assumed. The sails can either be standard, semi-rigid or rigid sails. Their aerodynamic performance is specified by the sail area and the sail lift coefficient, thus implying that the actual lift coefficient is ultimately determined by accounting for the sail drag. Ouchi et al. [10] and Smulders [11] have shown the feasibility of rigid wing sails with lift coefficients between 1.8 and 2.5. Kim and Park [8] proposed the use of parawings to exploit the larger wind power at altitude. Later, Kim and Park [9] showed the economic profitability of the concept through case studies. Also, the hydrodynamic drag of sailing vessels can be minimized by the use of hydrofoils.

2. Methodology and modeling

In the following sections only conventional single or multi-hull vessels are considered where the hydrodynamic drag is specified by the wetted area A_V and the hydrodynamic drag coefficient c_D. Also, the drag due to additional control surfaces and hydrofoils needed for ship stabilization is neglected. As can be seen in Fig. 1, the sail area is denoted as A and the turbine area as A_T. The relative wind velocity w produces the aerodynamic lift force L, which can be divided into the thrust T and the heeling force S. Due to the thrust the vessel speed V will adapt, which is also the inflow velocity of the hydrokinetic turbine under the assumption of no water velocity. The outflow velocity of the turbine is specified through the axial induction factor ζ, which is defined as the ratio of the inflow and outflow velocity and is therefore a measure of the flow deceleration through the turbine. The generated electricity is used to split sea water into hydrogen, which is compressed and stored in tanks. For a mathematical description the energy converter is separated into two functional units, each of them modeled by an axiomatic conversion law. The energy system, shown in Fig. 1, can be divided into the vessel propulsion system and the hydrokinetic turbine which is described through the disk actuator theory.

Without loss of generality a rigid sail is considered which produces the thrust T needed to propel the vessel. The thrust is balanced by both the drag force of the vessel $W = A_V c_D V^2 \varrho_l/2$ and the resistance force of the turbine W_T, leading to the force balance $T = W + W_T$. The drag force of the turbine is given by the momentum balance for the turbine $W_T = \Delta p A_T$ with the pressure difference determined by Bernoulli's equation $\Delta p = V^2(1-\zeta^2)\varrho_l/2$. For the first approach, the influence of the free surface is neglected. For a more detailed model the interaction of the free surface with the turbine should not be neglected as shown by the first author [12,13] and Metzler [13]. Also the tangential induced velocity, caused by the circulation on sail and turbine, are neglected. The theory considering the rotation of the stream tube is shown in detail by Schmitz [14] for wind turbines. Also, Fig. 2 shows the vessel and wind speed as well as the forces on a sail section.

Neglecting friction and induced drag for a first approach, the thrust force is given by the sine of the lift force

$$T = \sin\beta \, \frac{\varrho_g}{2} A \, c_L(\alpha) \, w^2, \tag{2}$$

β denotes the relative wind direction as shown in Fig. 2. w denotes the relative wind speed and c_L the lift coefficient, which is a function of the angle of attack α. The cosine rule gives a relation between the velocities at the sail section

$$w^2 = V^2 + c^2 - 2V\,c\cos\alpha_0, \tag{3}$$

where c denotes the absolute wind velocity and α_0 the absolute wind direction. The absolute wind velocity is the vector sum of the relative wind and the vessel speed $\vec{c} = \vec{V} + \vec{w}$. By introducing the dimensionless absolute velocity $v := V/c$, the dimensionless air density $\varrho := \varrho_g/\varrho_l$ (measured in multiples of the water density) the dimensionless thrust is given by

$$\frac{T}{\varrho_l c^2 A/2} = \sin\beta \, c_L \varrho \left(v^2 + 1 - 2v\cos\alpha_0\right). \tag{4}$$

By applying the dimensionless quantities, we end up with the dimensionless force balance

$$\sin\beta \, c_L \varrho \left(v^2 + 1 - 2v\cos\alpha_0\right) = v^2 c_D a_V + v^2\left(1-\zeta^2\right) a_T. \tag{5}$$

giving a relation between the dimensionless vessel speed and the axial induction factor of the turbine. Here the dimensionless areas are $a_V := A_V/A$ and $a_T := A_T/A$. Equation (5) is equivalent to

$$v^2 - 2vq\cos\alpha_0 + q = 0. \tag{6}$$

with the substitution

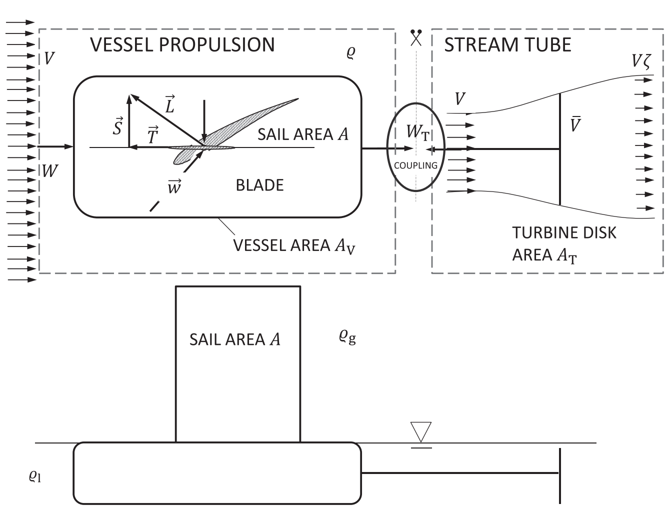

Fig. 1. Free-body representation of the energy ship.

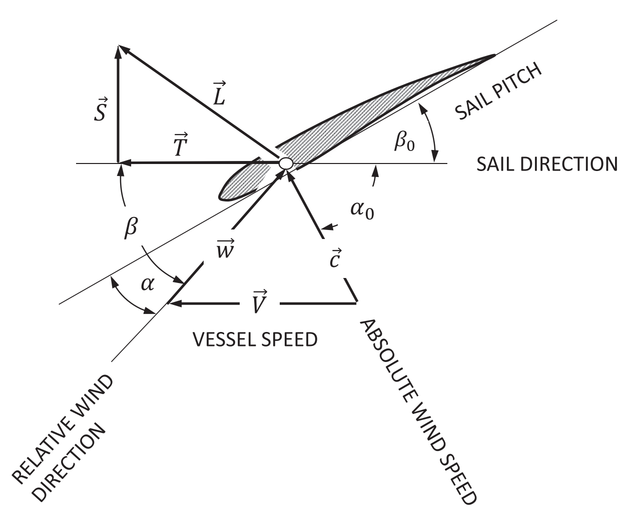

Fig. 2. Wind speed and forces on a sail section.