Renewable and Sustainable Energy Reviews 74 (2017) 424–437

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Hot-spots of large wave energy resources in relatively sheltered sections of the Baltic Sea coast

Olga Kovaleva[a,b,*], Maris Eelsalu[b], Tarmo Soomere[b,c]

[a] Immanuel Kant Baltic Federal University, Nevskogo str., 14, 238300 Kaliningrad, Russia
[b] Institute of Cybernetics at Tallinn University of Technology, Akadeemia tee 21, 12618 Tallinn, Estonia
[c] Estonian Academy of Sciences, Kohtu 6, 10130 Tallinn, Estonia

ARTICLE INFO

Keywords:
Wave power
Wave modelling
Baltic Sea
Gulf of Finland
Bay of Gdańsk

ABSTRACT

Even though semi-sheltered sea areas usually have limited wave energy resources, some regions of such basins may still be suitable for wave energy production. We provide a review of the existing wave energy studies in the Baltic Sea basin and discuss specific features and limitations for wave energy production in this water body and possible types of small-scale wave energy converters. We also extend the numerical analysis of wave energy resources in the Baltic Sea to some semi-sheltered nearshore sections that may host large levels of wave energy flux because of a specific combination of the wind regime and geometry of the sea. The test areas are located in the vicinity of the Bay of Gdańsk and in the eastern Gulf of Finland. The estimates of wave energy flux rely on numerically reconstructed time series of wave properties with a spatial resolution of 5.5 km along a > 200 km long coastal section. The average wave energy resource in the test areas is much lower than at the open eastern Baltic Sea coast. However, several sections of the test regions have wave energy potential comparable to fully-open nearshore areas. The onshore wave energy flux reaches 1.79 kW/m at the coast of the Sambian (Samland) Peninsula and 1.61 kW/m in selected sections of the north-eastern Gulf of Finland. These levels provide reasonable options for local wave energy production.

1. Introduction

Ocean waves are one of the most feasible sources of renewable energy [1]. While certain quantities of wave energy reach each coastal area, some locations are presently not favourable for (grid) energy production for various reasons, frequently due to the limitations of existing wave energy converters (WECs) [2]. Although the most promising parts of nearshore waters cover only 2% of the ocean shoreline, they may provide up to 480 GW of power output or 4200 TWh/yr of electricity generation [3]. This energy is fully renewable because it stems from solar power. The wind fields serve as a mediator and the water surface serves as a waveguide that channels the energy to the production site. Therefore, wave energy harvesting is associated with very low levels of pollution and CO_2 release and side effects (e.g., shifting of ship navigation routes or an increase in military importance of an area [4]) are minor.

Wave energy resources (per meter of coastline) are generally less beneficial in semi-sheltered water bodies such as the Mediterranean Sea [5,6], Black Sea [7] or the Baltic Sea [8,9]. Even though semi-sheltered sea areas usually have limited wave energy resources even on the European scale [10], some regions of such basins may still be suitable for wave energy production [11]. For example, some coastal segments may have large waves arriving from neighbouring open sea domains under certain wind directions [12]. Wave refraction in shallow areas may systematically lead to large concentrations of wave energy in the nearshore [13] and to the formation of unexpectedly rough wave conditions [14]. In some occasions it is possible to harvest wave energy from large areas [8] or to substantially reduce the energy cost using co-located wind and wave farms [15]. Wave energy harvesting at these locations (and sometimes even in relatively mild wave climates) may serve as an economically efficient way for the protection of certain structures [16,17]. The presence of systematic wind anisotropy may lead to reasonable wave energy resources in some coastal areas where long and high waves occur relatively frequently. In the Baltic Sea such areas are found in the nearshore of the north-western and south-western Baltic Proper [18].

Consideration of these matters together with emerging new technical solutions and small-scale devices that are able to accommodate steep waves and intermittent wave conditions [19] (see also http://www.earthtimes.org/energy/wave-power-generator-tested-black-sea-storm/2011/) reinforces the interest in wave energy potential in semi-sheltered sea areas. This potential has been studied in some detail for

* Corresponding author at: Immanuel Kant Baltic Federal University, Nevskogo str., 14, 238300 Kaliningrad, Russia.

http://dx.doi.org/10.1016/j.rser.2017.02.033
Received 23 July 2015; Received in revised form 1 February 2017; Accepted 6 February 2017
1364-0321/

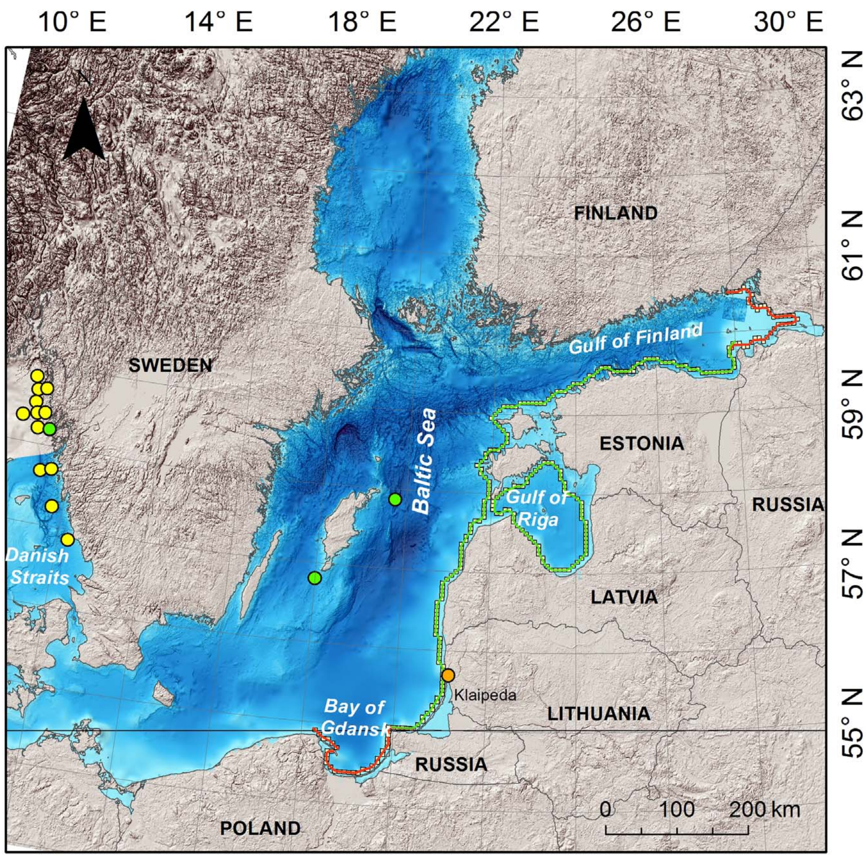

Fig. 1. Location scheme of the Baltic Sea areas for which the wave energy potential has been addressed in the literature. Small green squares cover the domain considered in [9]. Circles indicate localized study areas (orange [20], green [36], yellow [37]). The analysis for the Bay of Gdańsk and the eastern part of the Gulf of Finland (small red squares) is performed in this paper. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

the open eastern coast of the Baltic Proper and for some sections of the nearshore of the Gulf of Riga and southern Gulf of Finland based on numerical simulations [9] and long-term time series of visual wave observations [20].

In this paper we provide a review of the outcome of the existing wave energy studies in the Baltic Sea basin (Fig. 1). The focus is on the identification of locations (hot-spots) where wave energy flux is at levels favourable for wave energy production in the future. These areas are also the most vulnerable in terms of coastal erosion. As an important side effect of wave energy production, erosion prone locations may be partially protected against high waves by (chains or arrays of) WECs. We specifically explore the wave properties and prospective for wave energy production in two regions at the eastern coast of the Baltic Sea – the Bay of Gdańsk and the eastern part of the Gulf of Finland (Fig. 2) using the technique developed in [9]. We also discuss prospective designs of small-scale WECs and feasible ways for practical use of wave energy in the Baltic Sea conditions.

The paper is structured as follows. A review of the basic features of the Baltic Sea wave climate, the core quantities used to characterise the wave energy potential, the outcome of wave energy studies in this region and an insight into feasible designs of WECs are presented in Section 2. Section 3 describes the technique of evaluation of wave energy resource along longer coastal stretches from time series of wave height, period and propagation direction. It also gives a brief insight into the implementation of the wave model WAM, the output of which is used in the calculations. Section 4 describes the results of the evaluation of the wave energy potential and discusses the similarities and differences of the wave energy potential in the test areas (the Bay of Gdańsk and the eastern Gulf of Finland). Section 5 presents a short discussion of the outcome and Section 6 formulates the conclusions.

2. Wave energy potential in the Baltic Sea

2.1. Wave climate in the Baltic Sea basin

The core features of the Baltic Sea wave climate from the viewpoint of wave energy harvesting are: (i) relatively mild overall wave regime, (ii) predominance of comparatively short waves, (iii) marked anisotropy and (iv) high intermittency of wave fields, and (v) occasional presence of very rough seas.

The wave climate of the Baltic Sea is, on average, relatively mild [21]. The long-term significant wave height H_S slightly exceeds 1 m in the open part of the Baltic Proper. Wave heights are somewhat less between Gotland and the Swedish mainland and in the Bay of Bothnia. The wave climate is even milder, with H_S around 0.6–0.8 m in semi-sheltered sub-basins such as the Gulf of Finland, Gulf of Riga or Arkona Basin [21,22].

While regular swells are usually the best wave conditions for energy harvesting [1], strong long-period swells are infrequent in all parts of the Baltic Sea [18,23]. As characteristic to semi-sheltered water bodies, the predominant wave periods are considerably shorter in the Baltic Sea than in the neighbouring North Sea or the North Atlantic. Usually waves with periods of 4–6 s predominate in the Baltic Proper (where periods up to 7–8 s also often occur). The typical periods are even smaller, about 3–4 s in the more sheltered and coastal regions [21]. This means that WECs for this region should be designed for relatively steep waves.

The wave regime of the Baltic Sea is markedly anisotropic. This feature is caused by the presence of a two-peak directional structure of marine winds: strong winds predominantly blow from the south-west and north-north-west [24]. This anisotropic wind pattern leads to considerable wave energy concentration along the eastern coasts of the