Title	Hydrokinetic energy exploitation under combined river and tidal flow
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Publication date	2019-05-11
Original citation	Fouz, D. M., Carballo, R., Ramos, V. and Iglesias, G. (2019) 'Hydrokinetic energy exploitation under combined river and tidal flow', Renewable Energy, 143, pp. 558-568. doi: 10.1016/j.renene.2019.05.035
Type of publication	Article (peer-reviewed)
Link to publisher's version	http://www.sciencedirect.com/science/article/pii/S0960148119306949 http://dx.doi.org/10.1016/j.renene.2019.05.035 Access to the full text of the published version may require a subscription.
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Embargo information	Access to this article is restricted until 24 months after publication by request of the publisher.
Embargo lift date	2021-05-11
Item downloaded from	http://hdl.handle.net/10468/8200

1   Hydrokinetic energy exploitation under combined river and tidal flow

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8
9   **Abstract**

10   Hydrokinetic energy has been mainly studied in areas where the principal driver of the current is

11   the tide. However, in certain areas river discharges play also a principal role. The exploitation of

12   the hydrokinetic resource in such areas has its own peculiarities, dictated by the combined

13   influence of the two driving agents. The objective of this paper is to investigate the exploitation

14   of hydrokinetic energy in the Miño Estuary, the largest estuary in NW Spain and N Portugal,

15   with a focus on the site-specific performance of hydrokinetic energy converters (HECs) and its

16   intra-annual variability. A state-of-the-art hydrodynamics numerical model is implemented and

17   successfully validated based on field data. A third-generation HEC—to be more specific, the

18   new Smart Freestream Turbine (SFT)—is considered, and its performance at the location with

19   the greatest potential is assessed by means of: (i) site-specific efficiency, (ii) availability factor,

20   and (iii) capacity factor. We find that, whereas the site-specific efficiency does not vary

21   significantly, the availability and capacity factors do experience substantial intra-annual

22   (seasonal) variability. In summer and autumn, river discharges are low, and the tide dominates

23   the hydrokinetic resource. In contrast, during winter and spring, the river discharges

24   significantly contribute to the resource, leading to a considerable increase in the availability and

25   capacity factors. More generally, the results imply that in areas subject to combined fluvial and

26   tidal influences the performance of HECs may depart significantly from that in tide-dominated

27   areas, and this departure must be carefully weighed in assessing a project.

28

29   **Keywords**: hydrokinetic energy; tidal stream energy; river discharge; seasonal variability;

30   hydrokinetic energy converter

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1. Introduction

Global warming has drawn attention to new renewable ways of energy production based on principles of efficiency and sustainability [1]. As a result, hydrokinetic energy has been postulated as one of the most promising renewable energy sources that can be developed in the medium term due to its high potential and its reduced environmental impact [2-6].

The hydrokinetic resource is the result of different factors, namely: tidal currents, ocean currents, barotropic flows resulting from river discharges and baroclinic circulation, amongst others. The viability of its exploitation requires that peak velocities attain 1-1.5 ms^{-1} [7]. As a result, estuarine areas have emerged as a promising site for the exploitation of hydrokinetic energy, primarily resulting from the action of the tide which is enhanced by the complex geometry of semi-enclosed bodies [8-10]. Nevertheless, the influence of large river discharges on the available resource and their interaction with tidal flows have not been appropriately investigated.

On the other hand, the hydrokinetic resource can be harnessed by the so-called Hydrokinetic Energy Converters (HECs). According to the International Electrotechnical Commission (IEC) criterion, HECs can be classified in five main groups [11-15]: (i) devices with horizontal axis parallel to flow, (ii) devices with horizontal axis perpendicular to flow, (iii) devices with vertical axis, (iv) hydrofoils and (v) other devices. HECs are still currently under development and, as it is the case of other marine renewables [16,17], they are expected to become more economically competitive. Recently, a new generation of HECs has been developed, the so-called third generation devices [18], designed to operate in shallow areas with relatively low velocities and reduced depths (roughly 0.7 ms^{-1} of velocity magnitude and 1 m depth) —where hydrokinetic energy exploitation was not previously considered— and allowing the reduction of the environmental impact by using a compact generation equipment.

Planning of a new hydrokinetic energy farm should rely on the selection of the optimum device-location combination, which in turn should consider several aspects [19-21], as it is the case of other marine renewables [22-24]. This is of paramount importance in shallow areas with narrow sections given that, in addition to energy production considerations, the geometry imposes

2

59   strong limitations to turbine installation and operation [25-27]. In this context, the Galician

60   coast is characterized by a number of estuaries with complex geometry and, in some cases,

61   substantial freshwater discharges. River Miño is the most important fluvial course in this region.

62   Its estuary, with its main axis (Figures 1 and 2) extending over approximately 38 km [28] has a

63   total area of about 23 km^2 and an average depth of about 2.6 m [29]. The tidal regime is purely

64   semidiurnal, with a form factor [30] $F = 0.0932$ and a maximum tidal range of approximately

65   4.0 m (mesotidal). The estuarine circulation will be shown to be profoundly influenced by the

66   river discharge. The annual discharge is roughly 400 m^{3}s^{-1}, ranging from monthly minima of

67   100 m^{3}s^{-1} to monthly maxima of 1000 m^{3}s^{-1}. As a result of the action of the two major

68   hydrodynamic forcing factors (the tide and freshwater discharges) over its narrow and shallow

69   sections, this estuary presents significant current velocities, well in excess of 1 ms^{-1}, and

70   therefore constitutes a hotspot for hydrokinetic energy exploitation [31].

71

72   [FIGURE 1]

73

74   [FIGURE 2]

75

76   In this work, the hydrokinetic resource exploitation in the Miño Estuary is analysed by

77   considering the installation of a Smart Freestream Turbine (SFT). For this purpose, and

78   considering the high variability in the freshwater discharge, which may be expected to affect the

79   intra-annual performance of the SFT, the intra-annual spatio-temporal distribution of the current

80   velocities is computed by implementing a shallow-water numerical model. Then, by combining

81   the velocity data obtained by the numerical model with the power curve of the device, the intra-

82   annual energy production of SFT at three locations of interest [31] is computed (Figure 2).

83   Finally, having determined the SFT-site combination providing the largest energy production

84   amongst those previously selected, its performance is thoroughly analysed through a gamut of

85   performance parameters.

86 This paper is structured as follows: first, in Section 2, the methodology used in this work for

87 assessing the resource distribution and analysing the performance of the HEC selected is

88 thoroughly described; then, in Section 3, the results are presented and discussed focusing on

89 three main aspects: resource assessment, site selection and performance analysis; finally, in

90 Section 4, the major findings and conclusions are presented.

91

92 **2. Material and methods**

93 *2.1. Numerical model formulation*

94 The first step prior to proposing alternatives for installing a hydrokinetic turbine is to

95 thoroughly analyse the space-time distribution of the available resource. To this end, the

96 Delft3D FLOW model [32] is implemented for the Miño Estuary and validated by means of

97 field data. The model solves the Navier-Stokes equations under the shallow-water and

98 Boussinesq assumptions coupled to the transport equation, thereby allowing the computation of

99 both the barotropic and baroclinic circulation. The equations are solved in their 2DH form

100 [33,34]:

101

$$\frac{\partial \zeta}{\partial t} + \frac{\partial \left[(d+\zeta)U\right]}{\partial x} + \frac{\partial \left[(d+\zeta)V\right]}{\partial y} = Q , \tag{1}$$

$$\left.\begin{aligned} \frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - fV &= -g\frac{\partial \zeta}{\partial x} - \frac{g}{\rho_0}\int_{-d}^{\varsigma}\frac{\partial \rho'}{\partial x}dz + \frac{\tau_{sx}-\tau_{bx}}{\rho_0(d+\varsigma)} + \upsilon_h\nabla^2 U \\ \frac{\partial U}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + fU &= -g\frac{\partial \zeta}{\partial y} - \frac{g}{\rho_0}\int_{-d}^{\varsigma}\frac{\partial \rho'}{\partial y}dz + \frac{\tau_{sy}-\tau_{by}}{\rho_0(d+\varsigma)} + \upsilon_h\nabla^2 V \end{aligned}\right\}, \text{ and} \tag{2}$$

$$\frac{\partial (\zeta+d)c}{\partial t} + \frac{\partial \left[(\zeta+d)Uc\right]}{\partial x} + \frac{\partial \left[(\zeta+d)Vc\right]}{\partial y} = D_h\nabla^2 c - \lambda_d(d+\zeta)c + R , \tag{3}$$

102

103 where (1) represents the conservation of mass under Boussinesq's hypothesis; the pair of

104 equations (2) express the conservation of momentum along *x* and *y* directions; and (3) is the

105 transport equation, which is solved for temperature and salinity. In these equations ζ and d

106   represent the water levels and depth, respectively; u and v are the components of the velocity in

107   the directions x and y respectively; ρ and ρ_0 express the density and reference density of sea

108   water respectively; Q is the intensity of mass sources; f stands for the Coriolis parameter; v_h is

109   the horizontal eddy viscosity; τ_{bx} and τ_{by} are the shear stress components over the sea bottom,

110   and τ_{sx} and τ_{sy} the wind stress components on the sea surface; c represents the temperature or

111   salinity constituents; D_h is the horizontal eddy diffusivity; λ_d represents the decay processes of

112   first-order; finally, R stands for the source term.

113   Regarding the spatial discretisation, the model uses the Arakawa-C grid, consisting in a

114   staggered grid within which ζ is defined at grid cell centres, and u and v are determined at the

115   central points of the grid cell faces. With respect to the discretisation of the horizontal advection

116   terms, the Cyclic method is applied. Finally, temporal discretisation is carried out by using a

117   semi-implicit alternating direction implicit (ADI) algorithm.

118

119   *2.2. Numerical model implementation*

120   The finite difference mesh is a Cartesian grid with a spatial resolution of 100 x 100 m which

121   covers the whole estuary, including the intertidal zones and emerged areas, and extends offshore

122   up to a water depth of approximately 100 m. In this manner the outer boundary is far enough

123   that eventual numerical disturbances do not affect the study area (Figure 3). The model is run

124   with a time step of 1 minute, which according to the Courant–Friedrichs–Levy criterion is

125   sufficient to ensure numerical stability considering the mesh resolution adopted [35].

126

127   [FIGURE 3]

128

129   The bathymetry, kindly provided by Hydrographic Institute of the Navy, was complemented

130   with a digital terrain model with a resolution of 50 x 50 m commissioned by the Galician

131   Regional Government (Xunta de Galicia), which allowed the representation of the intertidal

132   areas. The accurate representation of shallow areas is of key importance given the sensitivity of

133   the hydrokinetic resource to variations in the water depth and geomorphological configuration

5

134   [36]. Figure 4 shows the bathymetry and topographic data as interpolated onto the

135   computational grid in the study area.

136

137   [FIGURE 4]

138

139   The oceanic open boundaries comprise the north, south and west limits of the grid, along which

140   the main harmonics [37] of the astronomical tide (Table 1) and the salinity and temperature of

141   the oceanic waters are imposed through Dirichlet boundary conditions. The freshwater input of

142   the River Miño is imposed at the inner estuary, defined by its total discharge along with salinity

143   and temperature characteristics.

144

145   [TABLE 1]

146

147   Previous works [31] have shown that the discharge of the River Miño presents a markedly

148   seasonal behaviour. On this basis, four case studies are defined based on the variability of the

149   flow discharge as provided by the Miño-Sil Hydrographic Confederation for an average year

150   (Table 2).

151

152   [TABLE 2]

153

154   In order to analyse the seasonal hydrodynamics, the model is used to simulate the

155   aforementioned four seasonal scenarios by considering the average characteristics of the

156   relevant forcing factors during each of these four periods. In addition, in order to capture the

157   variability resulting from the tide within each case, the model is run during a 14.75 day period

158   [33,35] (half synodic month), i.e., a complete spring-neap tidal cycle, preceded by an additional

159   spin-up period [38].

160

161   *2.3. Numerical model validation*

162   With the aim of validating the numerical model, computed velocity measurements are compared

163   with field data recorded by an Acoustic Doppler Current Profiler (ADCP) during a period of

164   approximately 22 days. Before comparing computed and measured data, observed velocities are

165   de-noised and vertically averaged by means of a Stationary Wavelet Transformation (SWT) of

166   db10 type belonging to Daubechies family [39-42]. Figure 5 shows the comparison between

167   simulated and measured data. Overall, the model accurately reproduces the hydrodynamics of

168   the estuary, with a high determination coefficient, R^2=0.85. In particular, the model captures the

169   variation induced by the action of the tide, with downstream and upstream velocities

170   corresponding to positive and negative values, respectively, along with the flow induced by the

171   river which leads to a significant asymmetry in the resulting currents.

172

173   [FIGURE 5]

174

175   *2.4. Hydrokinetic energy resource and HEC performance assessment*

176   The available power density from the kinetic energy of the water flowing through a vertical

177   cross-section perpendicular to flow direction per unit of time $p_{KE}(t)$ is given by [33]:

178

$$p_{KE}(t) = \frac{1}{2}\rho\alpha(t)\left[V(t)\right]^3 \tag{4}$$

179

180   where ρ represents the water density; $V(t)$ is the flow velocity averaged over the section per unit

181   of time; finally, $\alpha(t)$ is the energy coefficient which takes into account the velocity dispersions

182   through the water column being usually set as $\alpha(t) \approx 1$ [43].

183   The electrical energy output of a HEC, E_e, over a period of time, T, can be obtained by

184   integrating the power density over the period of interest as [35]:

185

$$E_e = \int_0^T A C_p \, p_{KE}(t)\,dt \tag{5}$$

186

187   where C_p is the power coefficient which represents the relationship between power available

188   and harnessed [44]; finally, A is the swept area.

189   It is important to consider that the above equations (Eq. 4 and Eq. 5) are theoretical expressions.

190   Real HECs only work within a specific range of velocities with a lower velocity threshold or

191   cut-in, V_{ci}, and upper threshold or cut-off, V_{co} [35]. The efficiency of HECs is provided by

192   device developers through its power curve. The main technical specifications and power curve

193   of SFT are shown in Table 3 and Figure 6, respectively.

194

195   [TABLE 3]

196

197   [FIGURE 6]

198

199   As a result, the energy output of the SFT-site combinations selected is straightforwardly

200   computed by combining the current velocity results obtained at the locations of interest and the

201   power curve of the SFT. As expressed in Eq. 5 the electrical energy output, E_e, is determined by

202   integrating the power output data with respect to time, which is computed for the four case

203   studies, each of them covering a 14.75-day period. Annual figures are obtained by considering

204   that the intra-seasonal resource distribution is appropriately characterized by the fortnightly

205   period, i.e.:

206

$$\left(E_{e,season}\right)_i = \frac{\left(E_{e,simulation}\right)_i}{T_{simulation}} T_{season} \tag{6}$$

$$E_{e,annual} = \sum_{i=1}^{4} (E_{e,season})_i \tag{7}$$

207

208   where $(E_{e,season})_i$ is the seasonal energy production for the i season; $(E_{e,simulation})_i$ represents the

209   energy production during the 14.75-day simulation period for the i season; $T_{simulation}$ expresses

210   the duration of the simulation period, i.e., 14.75 days; T_{season} stands for the duration of a natural

211   season; finally, $E_{e,annual}$ is the annual energy output.

212   Based on previous works [35,45-47], three performance parameters are selected for the analysis

213   of the SFT-site combination providing the largest amount of energy: (i) the site-specific

214   efficiency, (ii) the availability factor and (iii) the capacity factor.

215   The site-specific efficiency, η_e, was defined in previous work [35] as the ratio between the

216   electrical energy output, E_e, and the available energy at the site, E, over a reference period of

217   time:

218

$$\eta_e = \frac{E_e}{E} \tag{8}$$

219

220   The availability factor, A_f, is the ratio between the operation time, t_o (during which the flow

221   speed is between the cut-in and cut-off velocities of the HEC) and the total period considered, T

222   [46]:

223

224

$$A_f = \frac{t_o}{T} \tag{9}$$

225

226   Finally, the capacity factor, C_f, is the ratio between the electrical energy output of a device over

227   a given period, E_e, and the electrical energy output it would have produced, had it operated at its

228   nominal regime during the same period [47]:

229

$$C_f = \frac{E_e}{TP_R} \tag{10}$$

230

231   where T is the duration of the reference period and P_R is the rated electrical power of the device.

232

233 **3. Results and discussion**

234 *3.1. Resource assessment*

235 Once validated, the numerical model can be used to compute the flow throughout the estuary.

236 For this purpose, and in order to quantify the hydrokinetic resource and the influence of the

237 fresh water discharge, the model is run considering the combined effect of the main forcing

238 factors as defined in Section 2. The analysis of the results is focused on three specific sites of

239 interest for energy exploitation: Area I in the middle estuary and Areas II and III in the inner

240 estuary (Figure 2) [31].

241 Given that the aim of this work is to quantify the hydrokinetic energy production in the areas

242 proposed—and the influence of fluvial discharges on it—the numerical model was applied to

243 compute the flow patterns during a spring-neap tidal cycle for the four case studies defined

244 (Section 2); the results are presented in Figures 7, 8 and 9 for Areas I, II and III, respectively.

245 The highest velocities occur during winter, the season with the largest freshwater discharge,

246 with a gradual and significant reduction from spring to autumn due to the reduction in

247 freshwater discharges. The influence of the river inputs is clearly observed in winter, during

248 which upstream velocities virtually disappear. The gradual reduction in the river discharge

249 allows upstream velocities to develop, as is apparent from the presence of a clear second peak in

250 each tidal cycle in summer and autumn of almost the same intensity as during the ebb.

251

252   [FIGURE 7]

253

254   [FIGURE 8]

255

256   [FIGURE 9]

257

258 From the analysis of the variations in the flow speed in the three areas selected, the following

259 results are obtained. The largest reduction in flow speed from one season to the next, hereinafter

260 referred to as *seasonal reduction*, occurs from winter to spring, with average values of 0.40

10

261   ms^{-1}, 0.50 ms^{-1} and 0.35 ms^{-1} in Areas I, II and III, respectively, closely followed by spring and

262   summer seasons, with mean *seasonal reductions* of 0.20 ms^{-1}, 0.40 ms^{-1} and 0.33 ms^{-1} in Areas

263   I, II and III, respectively. In contrast, the *seasonal reduction* from summer to autumn is almost

264   negligible: 0.01 ms^{-1}, 0.02 ms^{-1} and 0.02 ms^{-1} for Areas I, II and III, respectively. These trends

265   are caused by the intra-annual reductions in freshwater discharges, roughly of 450 m^{3}s^{-1} from

266   winter to spring, 400 m^{3}s^{-1} from spring to summer, and 45 m^{3}s^{-1} from summer to autumn (i.e.,

267   approx. a reduction of 44%, 69% and 26%, respectively). In addition, it can be observed that

268   the geometrical characteristics lead to a different reduction in the magnitude of the currents

269   amongst the areas considered, the section with largest modifications being the narrowest ($\approx$165

270   m).

271   The aforementioned seasonal variations in flow speed result in large seasonal variations in the

272   available power density (Eq. 5). In Figure 10, the seasonal power density is plotted for the area

273   with the greatest resource (Area II). In accordance with the seasonal distribution of fluvial

274   contributions and resulting current velocities, winter is the most energetic season, reaching

275   values of up to 3.46 kWm^{-2}, with an average of 2.14 kWm^{-2}; in spring, the reduction in the

276   velocity magnitude results in a significant decrease in the power density with an average value

277   of 0.80 kWm^{-2}; finally, in summer and autumn the power density plummets due to the sharp

278   reduction in the river discharges, both seasons presenting similar figures: 0.22 kWm^{-2} and 0.19

279   kWm^{-2}, respectively.

280

281   [FIGURE 10]

282

283   *3.2. Site selection*

284   The energy production of the SFT at the locations of interest is computed by combining the

285   velocity magnitude results with the power curve of the turbine (Section 2) (Figure 11). As can

286   be observed, the greatest energy output would be obtained in Area II, with an annual figure of

287   2.26 MWh, considerably higher than that in Area III (0.96 MWh) and tripling the value of Area

288   I (0.73 MWh). Furthermore, the differences in energy production between areas differ markedly

289 during the year. The greatest differences are present in winter with a total energy production of

290 1.46 MWh, 0.62 MWh and 0.51 MWh at Areas II, III and I, respectively. In spring, a significant

291 reduction in the energy production relative to the winter values occurs with total figures of 0.53

292 MWh, 0.26 MWh and 0.19 MWh at Areas II, III and I, respectively; thereby the differences

293 between areas are accordingly smaller. Finally, in summer and autumn the energy output

294 plummets, with each season representing in all cases less than 10% of the production attained in

295 winter, and less than 30% of spring (e.g., the energy production during autumn at Area I would

296 be 1.39% of the winter figure).

297 On the bases of these results, Area II emerges as the site with the greatest potential for installing

298 a hydrokinetic turbine and therefore is retained for a thorough performance assessment.

299

300 [FIGURE 11]

301

302 *3.3. Site-specific performance assessment*

303 The following performance parameters of the SFT at Area II were computed: availability factor,

304 A_f, capacity factor, C_f, and site-specific efficiency, η_{ss}, (Section 2), based on the intra-annual

305 energy output results (Figure 12).

306

307 [FIGURE 12]

308

309 The good match between the operation requirements of the turbine and Area II, in particular its

310 low cut-in velocity (0.7 ms^{-1}), leads to high values of the availability factor throughout the year:

311 100% in winter, 73.89% in spring, 49.86% summer, and 48.06% in autumn. These figures

312 reflect the importance of the large river discharge in winter for the turbine performance,

313 generating outflow currents in excess of 0.8 ms^{-1} throughout winter (even during the flood tide),

314 and thus above the cut-in speed (0.7 ms^{-1}). The average annual availability factor is 67.95%,

315 which corresponds to a total of 5871 hours of operational time in a year.

316   On the other hand, the capacity factor, C_f, is the parameter most influenced by the seasonality:

317   60.15% in winter, 22.06% in spring, 6.22% in summer, and 5.00% in autumn. From these

318   values, the equivalent hours, E_h, (hours of energy production at nominal power) [35] are:

319   1299.24 h in winter, 476.50 h in spring, 134.35 h in summer, and 107.78 h in autumn. As a

320   result, and despite the low levels attained over the second half of the year (summer-autumn), an

321   annual value of 23.35% for the capacity factor, i.e., 2017 h of E_h, is achieved. These values are

322   considered acceptable in the case of other renewables (e.g., C_f > 20% in wind energy) [48,49].

323   Finally, the site-specific turbine efficiency presents a completely different behaviour, with little

324   seasonal variability: 40.18% in winter, 39.44% in spring, 40.16% in summer, 37.52% in

325   autumn, meaning that the level of adequacy of the turbine for the site is roughly similar

326   throughout the year.

327

328   **3.   Conclusions**

329   The hydrokinetic resource in many coastal areas is not only the result of the tide, but also of

330   other factors such as river discharges. As a case study of a fluvio-tidal coastal area, the Miño

331   Estuary was considered in this work. With this aim, a shallow-water numerical model of the

332   estuarine hydrodynamics, successfully validated against field measurements, was used to

333   investigate the exploitation of the hydrokinetic resource in the estuary.

334   Three sites (Areas I, II and III) were initially selected as suitable for installing a third-generation

335   SFT. The hydrological regime was found to produce a substantial seasonal variability. During

336   winter and spring river discharges dominate the hydrodynamics, to the point of precluding the

337   upstream flow during the flood throughout winter. In contrast, during summer and autumn, the

338   reduction in freshwater discharges allows the tide to dominate the hydrodynamics. Then, the

339   corresponding distribution of the power density was computed. It was found that the available

340   resource experiences a significant intra-annual variation with average power density values

341   during winter approximately ten times higher than during summer and autumn.

342   The most appropriate area for installing a hydrokinetic turbine amongst the three areas retained

343   (I, II and III) was selected based on their seasonal energy production values. The largest energy

344   production can be obtained in Area II, almost doubling the energy output of Areas I and III; the

345   seasonality, however, is considerable, with winter providing the lion's share of the energy

346   production.

347   Finally, the intra-annual figures of several performance parameters of interest for the SFT-Area

348   II combination were computed. All in all, from the results it can be concluded that the

349   hydrodynamic regime of Area II is suited to the characteristics of the turbine selected, for which

350   river discharges play a major role. In particular, its low cut-in velocity (0.7 ms^{-1}) leads to high

351   values of the availability factor throughout the year, with an average annual figure of 67.95%

352   and 100% in winter. Large river discharges during the rainy season (in winter and, to a lesser

353   extent, spring) result in downstream currents above the cut-in velocity even during the flood

354   tide, leading to high availability factors and, in general, good performance figures.

355   In sum, the results obtained indicate that in areas subject to both tidal effects and large river

356   discharges, the performance of HECs may differ significantly from tide-dominated areas, with a

357   substantial intra-annual variability that needs to be accounted for in planning the exploitation of

358   the resource.

359

365

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480

481 **Figure captions**

482 Figure 1. Location of the Miño Estuary on the Galician coast, NW Spain.

483 Figure 2. Miño Estuary, study area and ADCP location.

484 Figure 3. Area covered by the model grid.

485 Figure 4. Bathymetry and topographic configuration of the Miño Estuary as interpolated to

486 model grid.

487 Figure 5. Magnitude of current velocities measured by the ADCP (circles) and computed by the

488 model (line) projected along the main axis of the estuary during the validation period.

489 Figure 6. Power curve of SFT.

490 Figure 7. Magnitude of the current velocity at Area I throughout a 14.75-day spring-neap cycle

491 in the winter, spring, summer and autumn cases.

492 Figure 8. Magnitude of the current velocity at Area II throughout a 14.75-day spring-neap cycle

493 in the winter, spring, summer and autumn cases.

494 Figure 9. Magnitude of the current velocity at Area III throughout a 14.75-day spring-neap cycle

495 in the winter, spring, summer and autumn cases.

496 Figure 10. Power density at Area II throughout a 14.75-day spring-neap cycle in the winter,

497 spring, summer and autumn cases.

498 Figure 11. Annual electric energy output of SFT at Areas I, II and III.

499 Figure 12. Performance of SFT at Area II in terms of availability factor, capacity factor and site-

500 specific turbine efficiency.

Table 1

Table 1. Tidal constituents at the ocean boundary of the grid.

Constituent	Amplitude (m)	Phase (°)
M2	1.0654	76.5400
S2	0.3700	105.9200
N2	0.2251	57.5200
K2	0.1017	102.1200
K1	0.0743	66.2800
O1	0.0595	320.7100
P1	0.0215	57.5100
Q1	0.0195	265.4700
Z0	2.0687	0.0000

Table 2

Table 2. Case studies.

Season	Months	Average discharge (m^3s^{-1})	Average temperature (ºC)
Winter	January February March	1013.25	10.9
Spring	April May June	568.47	14.5
Summer	July August September	174.09	20.5
Autumn	October November December	129.21	14.9

Table 3

Table 3. Main technical specifications of SFT [D (m), rotor diameter; A (m^2), swept area; W (kg), turbine weight; V_{ci} (ms^{-1}), cut-in velocity; V_{co} (ms^{-1}), cut-off velocity; V_R (ms^{-1}), rated velocity; P_R (kW), rated power; L (m), device length; B (m), device width; H (m), device height; N, number of blades; ω (rpm), angular velocity].

Smart Freestream turbine			
D (m)	1.0	P_R (kW)	1.12
A (m^2)	0.8	L (m)	2.6
W (kg)	300.0	B (m)	1.1
V_{ci} (ms^{-1})	0.7	H (m)	1.1
V_{co} (ms^{-1})	3.1	N	3.0
V_R (ms^{-1})	2.0	ω (rpm)	90-230
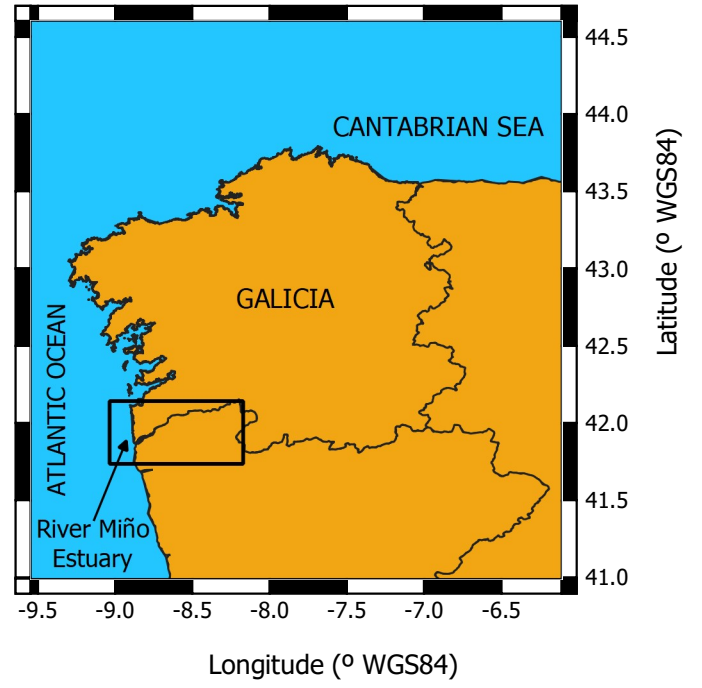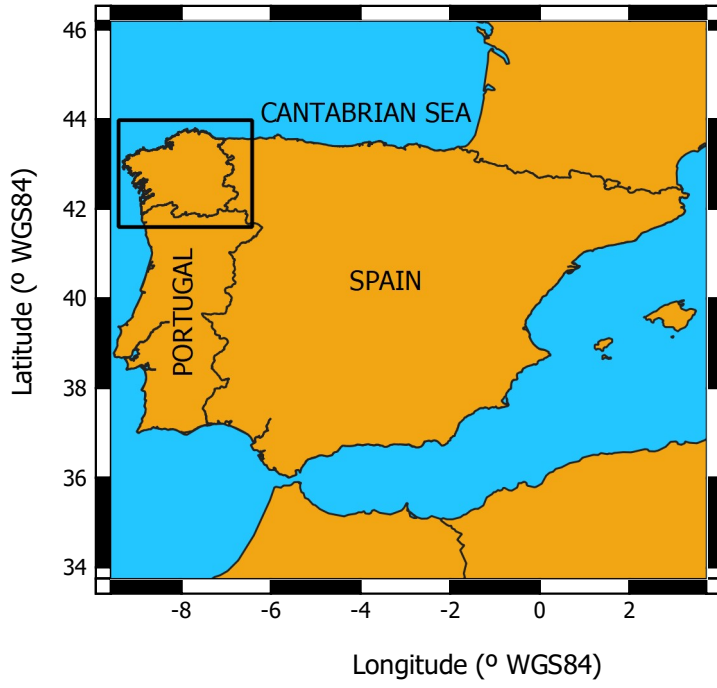
Figure 1

Figure 2
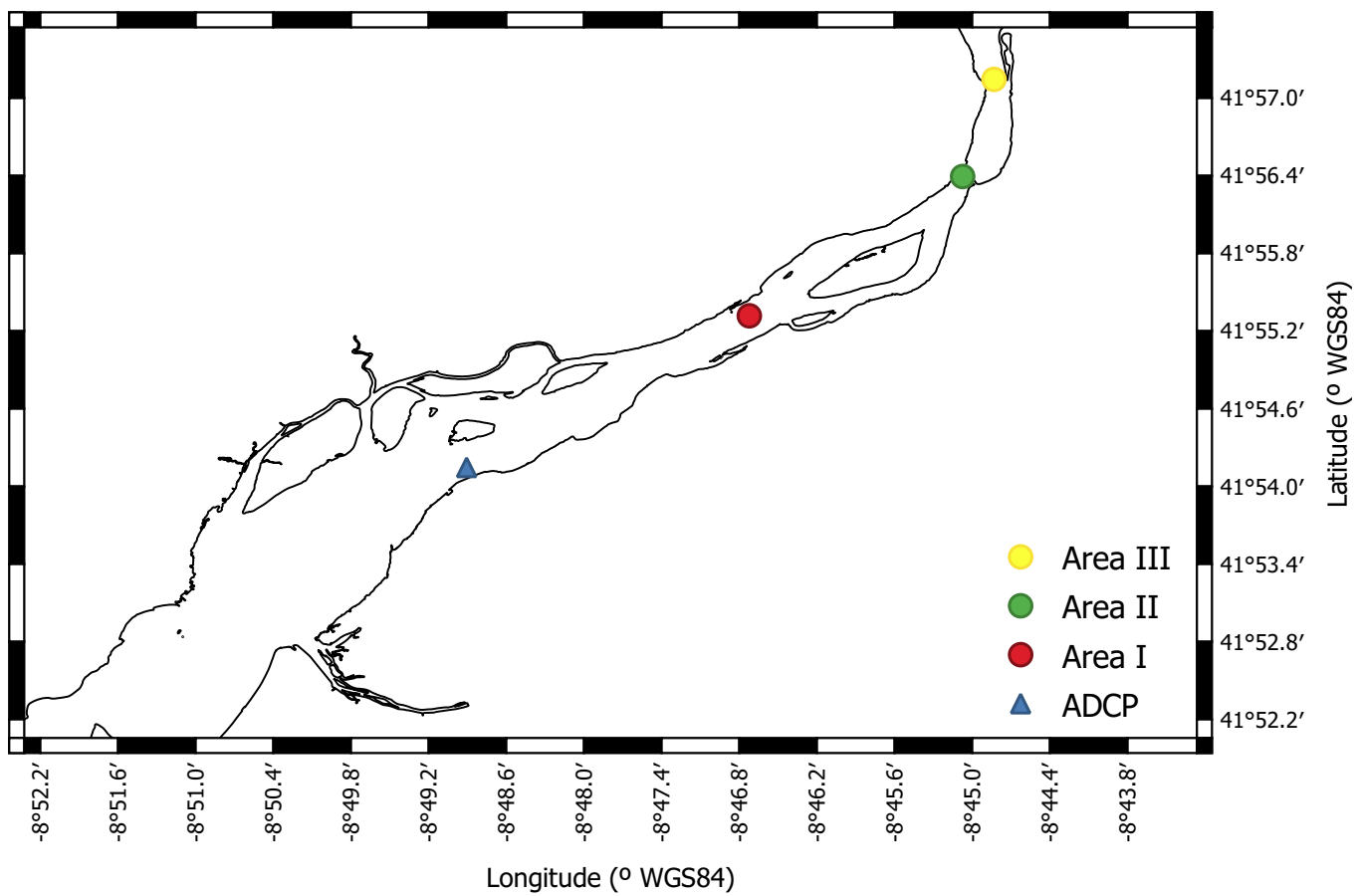
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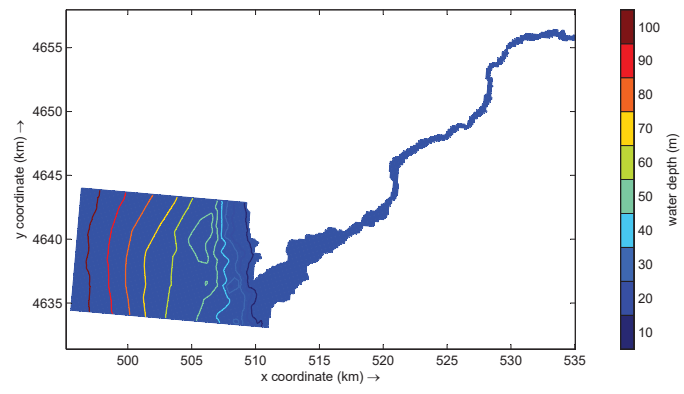
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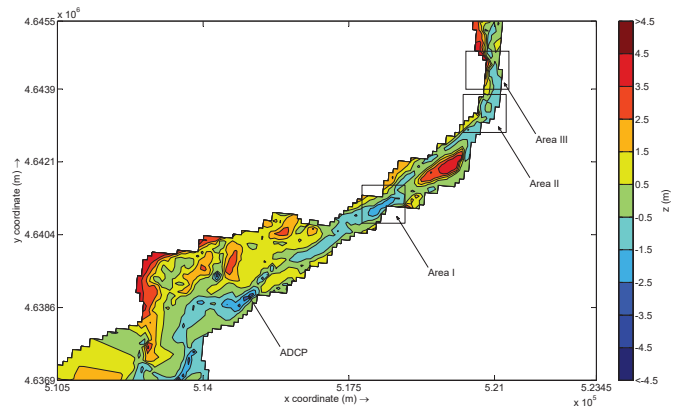
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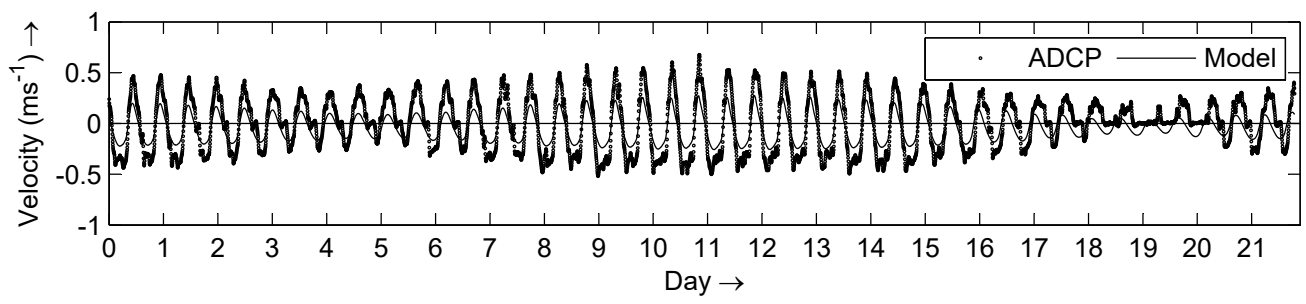
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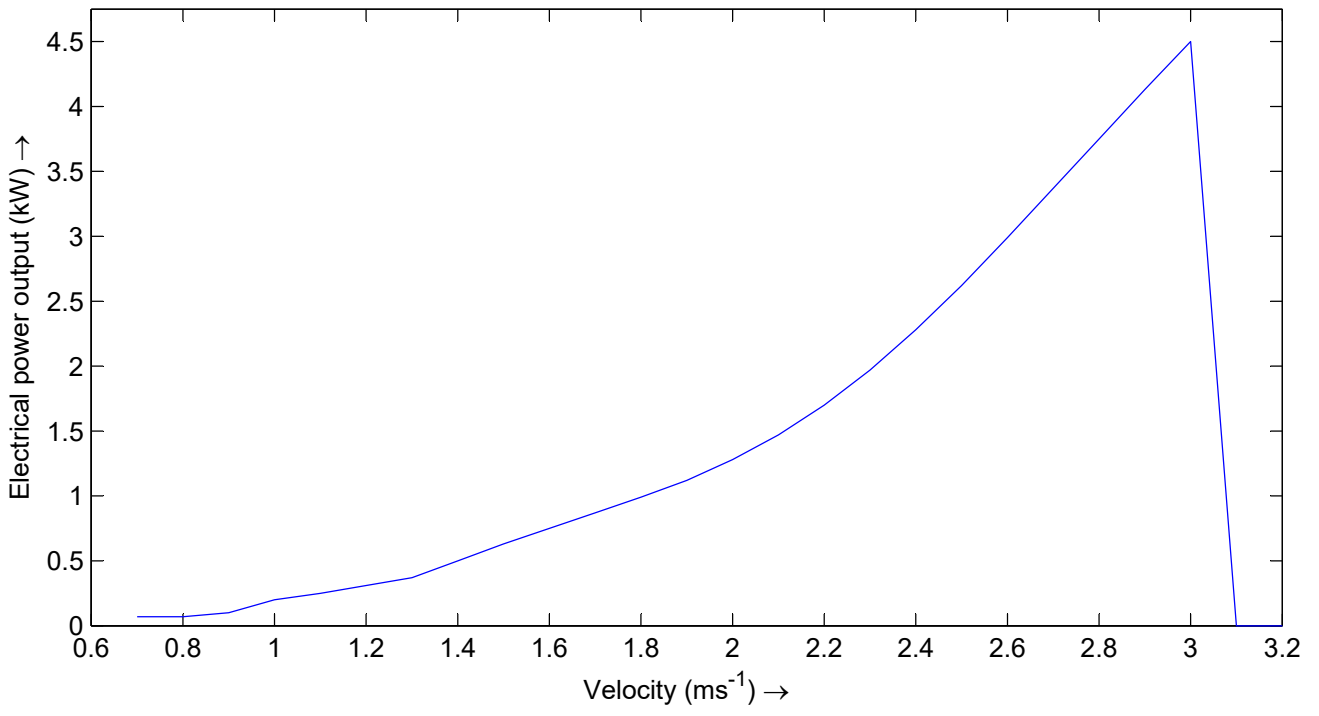
Figure 7
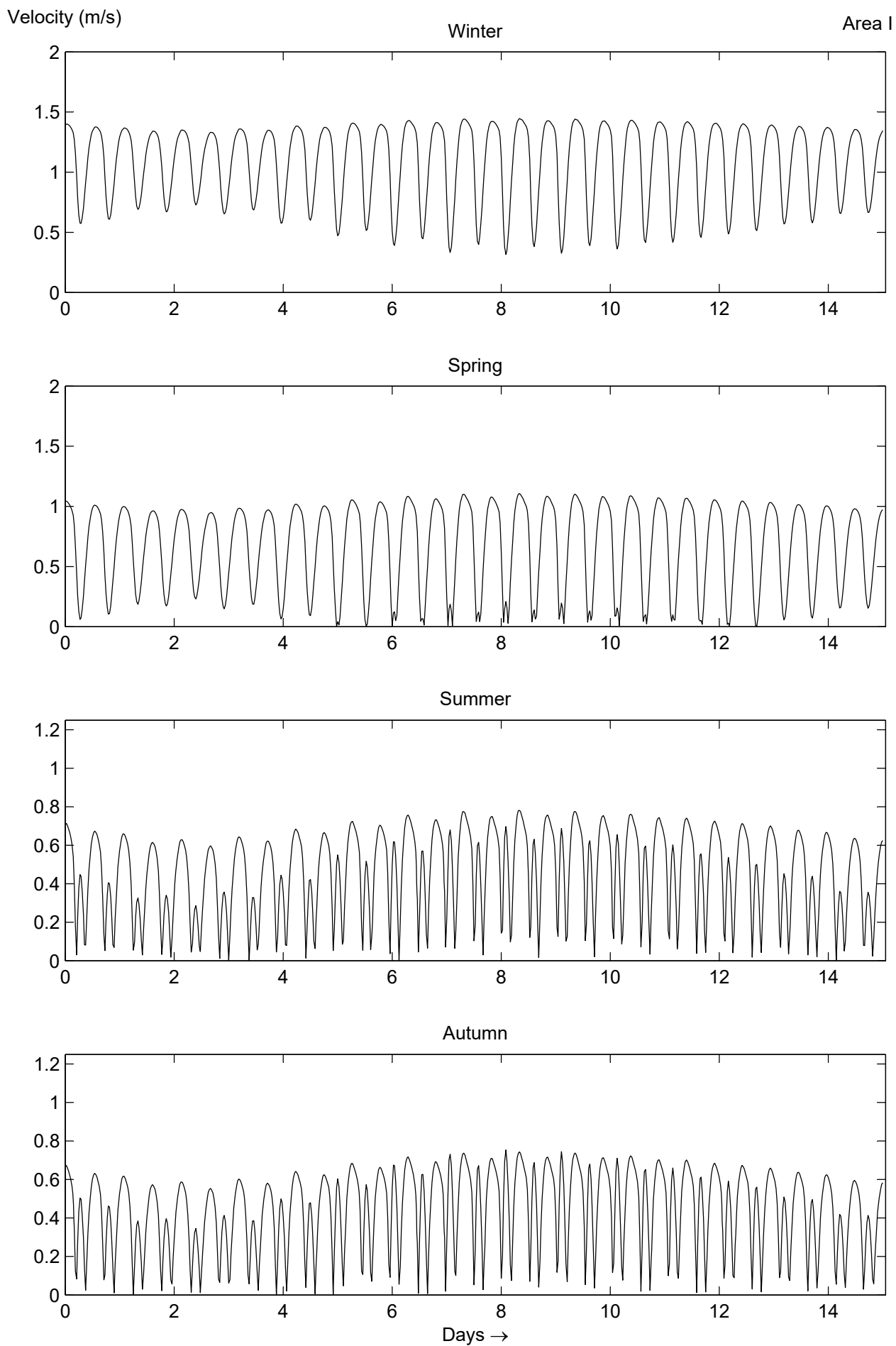
Figure 8

Figure 9

Figure 10

Figure 11

Figure 12