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Energetic and exergetic assessment of solar and wind potential maps in Europe

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Abstract

57 This paper deals with a physics-based assessment of renewable energy potential in
58 Europe, particularly solar and wind, using two literature models. A sensibility analysis
59 with the weather data is first-done. Actual temperature, pressure, RH, global radiation
60 and wind speed data are employed to develop energy and exergy maps for Europe,
61 based on iso-area of land-use. These maps are compared with similar existing ones.
62 Good agreement is obtained. A paradoxical result is obtained for wind exergy
63 efficiency. The yearly average exergy efficiency where wind speed is less than 5 m/s
64 is greater than the one where wind speed is greater than 7 m/s. This can be
65 explained by the “dome” shape of wind exergy efficiency. A solar efficiency map for
66 Europe is also developed and is a guide for choosing a renewable energy based on
67 yearly energy production.

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Keywords: Renewable Energy, Solar, Wind, Exergy, Energy, Efficiency, Map.

1 Introduction

75 Nowadays, European Union is considering renewable resources as major components of
76 future energy mix and has set more and more stringent objectives (see EC2009). Renewable
77 resources can be segmented by their converters: sun power (thermal or electric), wind
78 power, tide power, geothermic, hydraulic and bio-fuels. Clean energy cluster must be chosen
79 carefully and in relation with local context and constraints. Lovejoy (1996) described the
80 necessity of solar energy as regards population, finite resources (fossil or nuclear fuels) and
81 pollution. Use of renewable resources must challenge the intermittent production and a time
82 gap between production and consumption, see Sovacool (2009). Hoicka and Rowlands
83 (2011) have proposed to view solar and wind as complementary resources. Exergy analysis
84 is a smart tool for comparison between these different applications from a thermodynamic
85 point of view, providing a more relevant insight about the energy losses than an energy
86 analysis (Dincer 2002). Koroneos et al. (2003) have compared numerous types and uses of
87 energy solutions (Solar/Thermal, Wind/Electric, Geothermal, Solar/Electric and other non
88 renewable associations) using exergy analysis. They have essentially introduced the
89 following:

- 90
- The energy consumed in order to construct the plant, also called energy invested.

- 91 ▪ The energy produced, also called output energy.
92 ▪ The net energy produced is the difference between output energy minus energy invested.
93 ▪ The input energy is the primary energy, for example the energy received by the collectors
94 in case of solar thermal power systems, or the geothermal fluid energy in case of
95 geothermal power plants, and so on.

96 They also concluded the association Solar/Thermal has the best ratios compared to other
97 solutions: Net Energy Produced to Energy Invested and Output Energy to Input Energy.

98 Renewable resources (solar, wind and bio-fuels) can be seen as rival solutions
99 requiring ground, except off-shore installation. Table 1 summarizes their respective
100 advantages and drawbacks, see Kreith and Goswami (2007). Nevertheless, bio-fuels are still
101 a controversial solution since there is a risk of using the food resources to produce the bio-
102 fuels (Gasparatos et al. 2011). Consequently, we chose not to include this solution in this
103 paper.

104 Renewable sources can be considered in off-grid applications, often associated with a
105 diesel engine see Akyuz et al. (2009, 2011, 2012a), or connected to a national grid,
106 considered as an electric “well”, as in this paper.

107 The main aim of this paper is to define the exergy efficiency of solar and wind
108 converters over Europe as regards yearly production with an iso-area of land-use Based on
109 the literature review presented in section 2, the paper proposes two converter models, one
110 for each renewable resource (Joshi et al. 2009, and Pedersen et al. 1992). Meanwhile, a
111 study of sensibility is performed with relevant weather inputs (temperature, pressure, RH,
112 global radiation, wind speed). Yearly energy and exergy production maps are then
113 established over Europe and discussed in section 4. Such maps can be a useful tool for cost
114 analysis. Weather DOE database (Department of Energy, USA) available online is the
115 source to build a “typical” year for 8,760 representative hours over 20 years.

116 Furthermore, the paper focuses on the physics (thermodynamics) underlying the
117 energy options, in order to assess and compare their theoretical potentials according to
118 exergy and energy indicators. The aim is to provide an objective basis upstream to the
119 decision-making process, where the constraints specific to given projects would be taken into
120 account additionally in further stages (e.g., land use, visual impact, noise, infrastructure
121 requirements, etc.). Moreover, while the European Union has set targets for renewable
122 energy production at the European level, each Member State may implement its own policies
123 to meet its goals. Therefore, the economic and regulatory conditions (regulations, incentives,
124 etc.) vary from one country to the other. These aspects are thus not included in our analyses
125 either. This is indeed the topic for another field of literature (see e.g., Johansson and
126 Turkenburg 2004, Jäger-Waldau 2007).

127 Nevertheless, over Europe, it can exist areas where the competition between solar
 128 and wind energy can be effective in terms of yearly electric production; next the previous
 129 considerations can take place. For example in France, the common idea is: wind turbines are
 130 always a better solution in term of electric production and when constraints appear, you can
 131 resort to PV cells.

132
 133 **Table 1:** Advantages/Drawbacks of wind turbines and PV cells
 134

135 **2 METHODOLOGICAL BACKGROUND**

136 Several authors have developed exergy model to analyse renewable energy systems. For
 137 example, Sahin et al. (2006a and 2006b) have defined an exergy model of wind turbine
 138 systems and provided a spatio-temporal wind exergy map based on a dedicated description.
 139 Pope et al. (2010) have extended this approach by taking into account the type of wind
 140 turbines (horizontal or vertical axis). In parallel, Joshi et al. (2009) have proposed a model for
 141 a photovoltaic thermal system. They have also explained their methodology in terms of
 142 exergy analysis and weather dependences. This section reviews the theoretical background
 143 of these models and perform sensitivity analyses for the weather parameters in order to
 144 classify them according to their order of influence on the exergy efficiency.

145

146 **2.1 Solar energy option**

147 The exergy of global solar radiation can be performed as Jeter (1981) proposes:

$$148 \quad \dot{E}x^s = \left(1 - \frac{T_{amb}}{T_{sun}} \right) \phi_s A_{cell} \quad (1)$$

149 This exergy amount is spread out into an electric power and a thermal power. Electrical
 150 power is deduced as proposed by Joshi et al. (2009):

$$151 \quad \dot{E}x_e^s = \eta_{cell} \dot{E}x^s \quad (2)$$

152 The electric efficiency η_{cell} depends on the technology (crystalline or thin film, cell or
 153 module), see web site of University of Michigan. We use 12% as a default value, and we
 154 define its theoretical limit when comparing PV cell and HAWT, see section 4.3.

155 There are two possibilities for the estimation of thermal power \dot{Q}_{cell} , either by
 156 considering heat transfer as a function of wind speed, see Akyuz et al. (2012b) or by
 157 enthalpy balance based on mass flow rate of the flowing air (cooling system), see Joshi et al.
 158 (2009). For ensuring the model homogeneity, the thermal power \dot{Q}_{cell} is calculated with
 159 Joshi's approach:

$$160 \quad \dot{Q}_{cell} \approx \dot{m}_a C_{p_a} (T_{cell} - T_{amb})$$

161 where T_{cell} is estimated from Skoplaki et al. (2008) relation:

162 $T_{cell} = T_{amb} + k \phi_s$ (3)

163 Here k is the Ross coefficient and its value ranges from 0.021 (for free standing PV array
 164 mounting) to 0.054 (for opaque PV surface), see Skoplaki et al. (2008). Joshi et al. (2009)
 165 have used a k -value of 0.054 as the PV/T surface considered in their study was opaque.
 166 Since the correlation is simple and links T_{cell} with the ambient temperature and the incident
 167 solar radiation flux, it is appropriate for the prediction of the cell temperature, in a range of
 168 ambient temperature of [20-35°C], that means a range of cell temperature of [50-80°C].
 169 Consequently, the thermal exergy rate of PV cell is defined as

170 $\dot{E}x_{th}^s = \left(1 - \frac{T_{amb}}{T_{cell}}\right) \dot{Q}_{cell}$ (4)

171 The thermal exergy efficiency ψ_{th}^s is given by $\psi_{th}^e = \frac{\dot{E}x_{th}^s}{\dot{E}x^s}$. Then, PV cell exergy efficiency can

172 be defined as

173 $\psi^s = \frac{\dot{E}x_e^s + \dot{E}x_{th}^s}{\dot{E}x^s} = \eta_{cell} + \frac{\left(1 - \frac{T_{amb}}{T_{cell}}\right) \dot{Q}_{cell}}{\left(1 - \frac{T_{amb}}{T_{sun}}\right) \phi_s A_{cell}}$ (5)

174 Exergy efficiency of PV cell is decomposed by its electrical and thermal parts (using Joshi's
 175 model). Hence these exergies are plotted versus ambient temperature, see figure 1, and
 176 versus global solar radiation, see figure 2.

177 The higher the ambient temperature, the lesser the thermal exergy efficiency is, and
 178 consequently the lesser the total exergy efficiency is (by assuming that global solar radiation
 179 is constant), but this effect can be classified as a second order. For example, ambient
 180 temperature in the range of [0-30°C] involves a variation on total exergy efficiency in the
 181 "reverse" range of [32%-30%].

182 The higher the global solar radiation, the higher the thermal exergy efficiency is, and
 183 consequently the higher the total exergy efficiency is (by assuming that ambient temperature
 184 is constant). This effect is classified as a first order. For example, direct radiation in the range
 185 of 50-650 Wh m⁻² involves a variation on total exergy efficiency in the range of [13%-37%].

186
 187 **Figure 1:** Exergy efficiency for PV cell (Joshi's model): ambient temperature effect
 188

189 **Figure 2:** Exergy efficiency for PV cell (Joshi's model): global solar radiation effect
 190

191
 192 **2.2 Wind energy**

193 Wind kinetic energy is converted to electrical power by moving a wind turbine. Consequently,
 194 the instantaneous pressure drop ΔP , between upstream and downstream of the wind

195 turbine, can be modelled as two thermodynamic states, denoted by the subscript 1 for
 196 upstream and 2 for downstream.

$$197 \quad \Delta P(t) = P_1(t) - P_2(t) \quad (6)$$

198 Let's assume that firstly the linear turbine speed, noted V , is the average between up- and
 199 down-stream:

$$200 \quad V = \frac{V_1 + V_2}{2} \quad (7)$$

201 and secondly $\frac{V_2}{V_1}$ is small.

202 Then, by using the Barré de St Venant equation, one can write by neglecting enthalpy
 203 variations:

$$204 \quad \frac{P_1}{\rho} + \frac{V_1^2}{2} = \frac{P_2}{\rho} + \frac{V_2^2}{2} \Rightarrow V^2 = \frac{2}{\rho} \Delta P \quad (8)$$

205 Sahin et al. (2006a) have described a wind turbine model by adapting the wind chill
 206 temperature to this application:

$$207 \quad T_{windchill,i} = 35.74 + 0.6215 T_a - 35.75 V_i^{0.16} + 0.4274 T_a V_i^{0.16} \quad (9)$$

208 where $i \in \{1, 2\}$.

209 Thermodynamic states and specific "thermodynamic" exergy function of wet air are detailed
 210 by Dincer and Rosen (2007):

$$211 \quad ex^{th} = (Cp_a + \omega Cp_v) T_0 \left[\left(\frac{T}{T_0} \right) - 1 - \ln \left(\frac{T}{T_0} \right) \right] + (R_a + R_v \omega) T_0 \ln \left(\frac{P}{P_0} \right) + \\ T_0 \left[(R_a + R_v \omega) \ln \left(\frac{R_a + R_v \omega_0}{R_a + R_v \omega} \right) + R_v \ln \left(\frac{\omega}{\omega_0} \right) \right] \quad (10)$$

212 with R_a the air gas constant ($R_a = 287 \text{ J/kg K}$), R_v the water gas constant
 213 ($R_v = 461.5 \text{ J/kg K}$), Cp_a the specific heat of air (1002 J/kg K) and Cp_v the specific heat of
 214 vapour at reference temperature (1869 J/kg K at 25°C). Subscript 0 refers to dead state
 215 corresponding to ambient conditions; see Gaggioli (2012) or Sogut et al. (2009).

216 Then, exergy function is

$$217 \quad Ex^{th} = \dot{m} ex^{th} \quad (11)$$

218 where the specific humidity ratio:

$$219 \quad \omega = \frac{\dot{m}_w}{\dot{m}} \quad (12)$$

220 where \dot{m} is obtained with the continuity equation:

$$221 \quad \dot{m} = \rho A_w V \quad (13)$$

222 Golding (1955) has established the maximum power \hat{W} that can be extracted for given
 223 weather conditions:

224 $\hat{W} = \frac{8}{27} \rho A V_1^3$ (14)

225 Horizontal-axis wind turbines (HAWT), a more realistic model for power \dot{W} , is provided by
 226 Pedersen et al. (1992), see figure 3. This model of electric power versus wind speed is
 227 proposed for an optimal pitch angle and angle of attacks, see Thumthae and Chitsomboon
 228 (2009) for their definitions. To omit the wind direction, the authors assume that HAWT is
 229 equipped with yaw bearing system and untwisted blade. HAWT features are: rotor diameter
 230 18m, hub length 30m, nominal power 100 kW.

231 **Figure 3:** Electric power versus wind speed for HATW (Pedersen’s model)

232
 233
 234 The electric efficiency of wind turbine is defined by the ratio between its power and its
 235 maximum power and is plotted in figure 4:

236 $\eta = \frac{\dot{W}}{\hat{W}}$ (15)

237 It is very important to highlight that such a wind turbine has its maximum electric efficiency
 238 for a wind speed of around 8 m/s. Beyond this limit the power increases with wind speed but
 239 the efficiency decreases.

240 Then, wind exergy efficiency can be defined as:

241 $\psi^w = \frac{\dot{W}}{\Delta\left(\frac{1}{2}\dot{m} V^2 + Ex^w\right)} = \frac{\dot{W}}{\frac{1}{2}\dot{m} (V_1^2 - V_2^2) + Ex_1^w - Ex_2^w}$ (16)

242 Note that Hellmann equation gives the wind speed correction taking into account wind
 243 turbine hub:

244 $V_{corr} = V_{meas} \left(\frac{H}{H_{meas}}\right)^\alpha$ with $\alpha = 0.28$ (17)

245 For this model, instantaneous ambient conditions are defined by: temperature, wind speed,
 246 pressure and relative humidity. Then, the weather database of DOE is required to perform
 247 the sensitivity analyses.

248 Energy efficiency of HATW (using Pedersen’s model), see Eq (15), is plotted in
 249 Figure 4. Maximum energy efficiency, 50%, corresponds with 8 m/s. The transfer function
 250 between wind speed and electric efficiency is non linear and its shape is like a “dome”: a
 251 same value of energy efficiency can correspond with a low or a high wind speed, and thus a
 252 low or high electrical power. Therefore, an analysis of HATW energy efficiency cannot be
 253 done in a straightforward manner. It requires to set first either the wind speed or the electric
 254 power.

255

256

257 **Figure 4:** Electric efficiency for HATW (Pedersen's model)

258
259 Typical values of pressure variations between upstream and downstream (ΔP as defined by
260 eq(1)) and temperature variations are given in Table 2.

261
262
263 **Table 2 :** Pressure and temperature variations

264
265 Exergy efficiency of HATW (using Pedersen's model), see Eq (16), is plotted in Figure 5-
266 a). The shape between exergy efficiency of HATW (Pedersen's model) and wind speed is
267 approximately the same as previously, with its maximum exergy efficiency, around 35%, for a
268 wind speed of 7m/s, in the specified conditions. It is worth to propose a parametric study of
269 exergy efficiency as regards these conditions:

- 270 ■ Ambient temperature effect on exergy efficiency is plotted in Figure 5-b). This effect is
271 very significant and must be associated to the wind chill temperature. This effect can
272 be classified as a first order.
- 273 ■ Ambient pressure and relative humidity effects on exergy efficiency are plotted in
274 Figure 5-c) and Figure 5-d) respectively. These effects are not significant and are
275 classified as a second order. The slopes are $20 \cdot 10^{-6}$ for ambient pressure and $-4.6 \cdot 10^{-8}$
276 for relative humidity.

277
278 **Figure 5:** Exergy efficiency for HATW (Pedersen's model): a) wind speed effect,
279 b) ambient temperature effect,
280 c) ambient pressure effect, and
281 d) relative humidity effect.

282
283 **3 CASE STUDY FOR EUROPEAN UNION**

284 Using Joshi's model for PV cells and Pedersen's model for HATW, we computed the exergy
285 efficiency for average weather conditions of a set of locations across Europe. As an example,
286 data and results (exergy efficiencies for PV cells and wind power) for Paris (France) are
287 detailed in this section.

288 The models require weather data:

- 289 - wind speed
- 290 - ambient temperature
- 291 - ambient pressure
- 292 - global radiation
- 293 - relative humidity

294 These data are available on DOE website for various meteorological stations and for a
295 "representative" year with its 8760 hours. This choice requires more CPU-time than monthly

296 data, but it avoids introducing additional uncertainties due to the estimation of data
297 distribution, see Coskun et al. (2011).

298 An assumption was also needed to take into account the difference in the land use for
299 both systems (solar PV and wind power). A usual building layout of wind turbines is a
300 separation of at least around 5 times the rotor length to avoid fluid mechanic interactions.
301 Then, in this study, the authors have considered that the PV cell area is 5 times the cross
302 area of the wind turbines, that is to say 1,200m². Cumulative energy or exergy have been
303 calculated for this surface.

304 The exergy efficiency defined from Joshi's model for PV cells is a function of ambient
305 temperature and direct radiation, see figure 6. As explained before, ambient temperature has
306 a second order effect, then the main relation between this exergy efficiency and global
307 radiation is mostly independent of ambient temperature.

308
309 **Figure 6:** Total exergy efficiency of PV cell versus direct radiation for Paris
310
311

312 The wind speed over 8760 hours is plotted in Figure 7-a): the wind speed range is [0-
313 20] m/s. Statistical tools are commonly used to analyse such data: the cumulative normal
314 distribution of hourly wind speed in interval $[v_j; v_{j+1}]$ is the number of times that the hourly
315 wind speed (based on DOE database) occurs in this interval over the year. Same procedure
316 is applied to wind power. Figure 7-b) gives information about cumulative normal distributions
317 of hourly wind speed (see Kantar and Usta (2008), Ulgen and Hepbasli (2002)) and its
318 associated wind power. These distributions show clearly the gap between hourly distribution
319 and power distribution, hence 25% of the energy is produced only during 3% of the year
320 where the wind speed is 11 m/s. Such a gap was well expected, see Chang (2010). Monthly
321 wind direction is showed for three months (January, May and June) and reveals very large
322 orientation discrepancies, see Figure 7-c).

323
324
325 **Figure 7:** a) Representative year of wind speed for Paris
326 b) Cumulative normal distribution of wind speed and its associated wind power for Paris
327 c) Monthly wind direction for three months (January, May and June) for Paris
328

329 In this study, authors assume that HAWT are well oriented as regards wind
330 distribution. The monthly average temperatures are plotted in figure 8-a), and its range is [3-
331 25]°C. The monthly direct radiation is plotted in figure 8-b).

332
333 **Figure 8:** a) Monthly ambient temperature at Paris
334 b) Monthly direct radiation at Paris

335 The exergy efficiency for HAWT (using Pedersen's model) is a function of ambient
336 conditions as well. But there are crossed effects not so obvious. In Figure 9, the wind exergy
337 efficiency is plotted (for Paris):

- 338 - versus wind speed: as expected, the faster the wind speed, the greater the wind exergy,
339 but this observation is within an envelope: this shape shows a first order effect, see
340 Figure 9-a).
- 341 - versus ambient temperature: an upper linear limit seems to exist. There is a significant
342 scattering then these coupled effects are important, see Figure 9-b).
- 343 - versus ambient pressure: this parameter has a second order effect, then no tendency can
344 be proposed, see Figure 9-c).
- 345 - versus relative humidity: same comment as for ambient pressure, see Figure 9-d).

346

347 **Figure 9:** Hourly exergy efficiency of HAWT

348
349
350
351
352

- a) versus wind speed
- b) versus ambient temperature
- c) versus ambient pressure
- d) versus relative humidity

353 More than 100 meteorological stations have been considered, see figure 10, to represent
354 Europe. Spline interpolation is performed with common Sandwell algorithm (1987).

355

356

Figure 10: Location of meteorological stations over Europe

357

358 **4 RESULTS AND DISCUSSION**

359 **4.1 Primary exergy**

360 By "primary exergy", authors mean the exergy amount: this amount is calculated by eq (4) for
361 solar resources, and by eq (11) for wind resources. A cumulative amount is then computed
362 over the year, see Figures 11.

- 363 • The European Commission's Joint Research Centre in Ispra published an interactive
364 map of Europe (and Africa) showing the photovoltaic solar electricity potential, see EC
365 website. Figure 11-a) shows the latitude 45° as a good limit. Two singular locations must
366 be underlined: one near London (UK) and a second one near Göteborg (Sweden).
- 367 • An European Wind Atlas has been published for the European Commission by the Risø
368 National Laboratory, see EWA website. Wind "primary exergy" is very significant on the
369 west coast and especially in Ireland, see figure 11-b). On Mediterranean coast, an
370 important wind, called "mistral", blows near Marseille (France). EWA wind zones have
371 been plotted in dotted lines in Fig 11-b). These zones have a good concordance with
372 these obtained by our computations.

373

374
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Figure 11: Primary exergy from a) sun and b) wind resources

378 **4.2 Real conversion**

379 Cumulative electric power is performed from eq (2) for sun resource and by using eq (15) for
380 wind resource (with weather inputs from DOE database).

- 381 ▪ For sun resource, real cumulative electric power is plotted in Figure 12-a). With an
382 electric efficiency of 12%, the maximum cumulative electric power is only 240 MWh/y,
383 under the latitude 45°.
- 384 ▪ For wind resource, real cumulative electric power is plotted in Figure 12-b). In this
385 configuration, the maximum cumulative electric power is around 600 MWh/y. Its electric
386 conversion benefits from the number of hours of availability for the considered resource.

387
388
389

Figure 12: Yearly electric production a) solar resource b) wind resource

390 Electric energy predicted from wind resource versus sun resource for each meteorological
391 station is plotted in Figure 13. On this plot, the first bisectrix line has been added and y-axis
392 has been reshaped. Below this bisectrix line, one can determine few stations (in Austria:
393 Innsbruck and Linz, in Italia: Messina, Valence and Venice, in Slovakia: Brastilava, in Spain:
394 Valencia, and in Roumania: Cluj and Constanta) where sun resource could be interesting in
395 term of electric energy.

396
397
398
399

Figure 13: Wind energy potential versus sun energy potential for the 100 meteorological
stations tested

400 Exergy efficiencies are then detailed as follows:

- 401 ▪ Solar exergy efficiency, averaged over the year, is calculated from eq (5) and plotted in
402 figure 14-a). Since electrical efficiency is taken as 12%, this plot shows that “thermal
403 exergy efficiency” is in the range [5-15]%. A point worth mentioning here is that the
404 combined heat and power production from a PV/T system would increase the usability of
405 the system. Also a good electrical efficiency can be maintained throughout the day as the
406 thermal exergy from the system would have affected the latter adversely otherwise
407 removed from the PV panels.
- 408 ▪ Wind exergy efficiency, averaged over the year, is calculated from eq (16) and plotted in
409 Figure 14-b). This plot must be very carefully read because HAWT exergy efficiency
410 against wind speed is roughly a parabolic shape (see figure 5-a)). Indeed, the maximum
411 exergy efficiency is obtained for a wind speed around 7m/s. while the maximum electric
412 production is achieved for 13.5m/s. In other words, West Ireland coast can produce the

413 greater amount of electricity but its exergy efficiency is lower than other places (where
414 the wind speed is closer to 7 m/s). This point underlines that wind turbines must be
415 designed for the place where they are located. Since no heat is recoverable by this
416 converter, wind exergy efficiency is lower than the sun one. But in practice, most of the
417 PV systems do not recover the “waste” heat either.

418
419
420

Figure 14: Yearly exergy efficiency a) solar resource b) wind resource

421 **4.3 Solar/Wind electric production challenge**

422 As shown in the previous results, solar resource is more penalized by its intermittent feature
423 than wind resource. It is then interesting to ask: What would be the required solar electric
424 efficiency to exceed HAWT electric production? Knowing HATW electric production and
425 available direct radiation both cumulated over year, the ratio of both would give this solar
426 electric efficiency theoretical threshold. Solar efficiency theoretical thresholds are plotted in
427 figure 15 for the locations tested.

- 428 • Near North Sea coasts (France, Belgium, Germany, The Netherlands), Baltic sea coasts
429 and UK, the solar efficiency theoretical threshold would be over 40%. 40% is beyond the
430 current technological limits for solar efficiency, which is about 30% see MU web site.
431 Consequently, solar production can not challenge wind production in these regions.
- 432 • Near Mediterranean Sea coast in France, wind resource called “mistral” is in competition
433 with solar resource since real electric efficiency is nowadays technologically feasible
434 since the solar electric efficiency theoretical threshold can be met with current
435 technology.
- 436 • Above the latitude 45° , solar resource can already produce more electricity than wind
437 resource.

438 This paper just provides a tendency, not an exact result: an assessment for a specific
439 application is still required to go further in the decision process.

440
441
442

Figure 15: Solar electric efficiency theoretical threshold

443 **5 CONCLUSIONS**

444 Solar and wind resources have extensively been studied over Europe in terms of: available
445 resources, real conversion, and exergy efficiency. To achieve these maps, a complete study
446 of influencing parameters is firstly performed using two classical models (Joshi’s model for
447 PV cells and Pedersen’s model for HATW). Global radiation is the main parameter for PV
448 cells’ model and wind speed for HATW model. Ambient temperature is a major parameter for
449 exergy calculations for both. Hourly weather DOE database are used for Europe and
450 compared qualitatively to the literature data and maps. Then, we obtain with the DOE

451 database the maps of renewable resources over Europe. For solar resource, the latitude 45°
452 is clearly a limit to produce a significant amount of electricity. For wind resource, 4 regions
453 (North sea coasts, Baltic sea coasts, a specific coast of Mediterranean sea and UK) are very
454 effective for electrical production.

455 To challenge wind resource by solar resource, authors have evaluated a theoretical
456 PV electrical efficiency threshold. If one accepts a maximum value of electric conversion
457 efficiency around 40%, the previous four regions are not effective for solar energy (whatever
458 the technological progress). This result, more or less intuitive, is consequently established on
459 a thermodynamic point of view with the DOE weather database without any cost
460 consideration. Renewable energy is sometimes more ideological than scientific. Then this
461 kind of study could be complete by economic and regulatory conditions (regulations,
462 incentives, etc.) to be useful for decision makers.

463

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542

543 **Nomenclature**

544 Symbols

545	A	rotor swept area	$[m^2]$
546	A_{cell}	cell area	$[m^2]$
547	C_p	heat capacity at constant pressure	$[J\ kg^{-1}\ K^{-1}]$
548	\dot{E}_x	exergy rate	$[W]$
549	P	pressure	$[Pa]$
550	\dot{Q}	thermal power	$[W]$
551	R	specific gas constant	$[J\ kg^{-1}\ K^{-1}]$
552	T	temperature	$[K]$
553	V	speed	$[m\ s^{-1}]$
554	\dot{W}	wind turbine power	$[W]$
555	ex	specific exergy	$[J\ kg^{-1}]$
556	\dot{m}	mass flow rate	$[kg\ s^{-1}]$
557	t	time	$[s]$

558

559 Greek letters

560	Δ	difference	
561	Ψ	exergy efficiency	
562	η	energy efficiency	
563	ϕ	direct solar radiation	$[W\ m^{-2}]$
564	ρ	density	$[kg\ m^{-3}]$
565	ω	specific humidity ratio	

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567 Subscripts

568	0	means reference conditions, i.e. ambient conditions
569	1	upstream
570	2	downstream
571	V	referred to water vapor
572	a	referred to air
573	e	electric
574	i	index
575	amb	ambient conditions
576	cell	solar PV cell
577	corr	Hellmann's correction
578	meas	mean measurement conditions
579	sun	sun
580	windchill	wind chill

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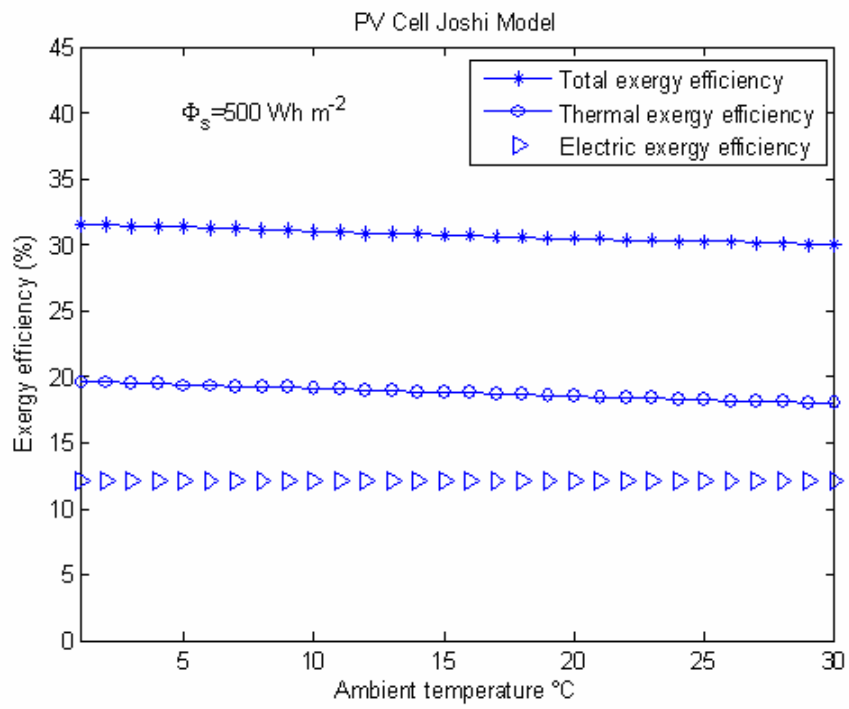
582 Exponents

583	th	thermodynamic
584	W	wind
585	S	solar

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587 Notation

588	\wedge	maximum
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Figure 1: Exergy efficiency for PV cell (Joshi's model): ambient temperature effect

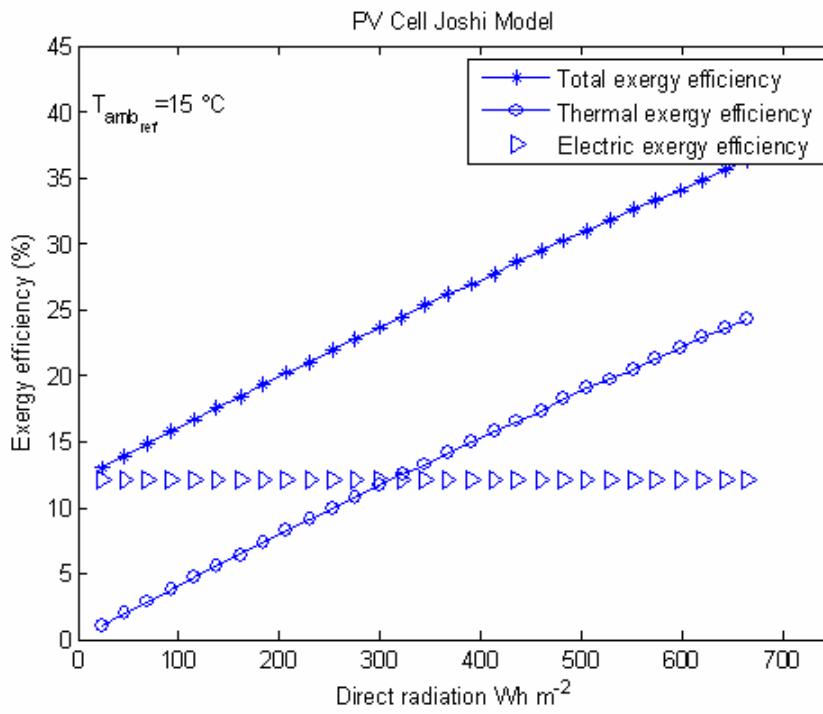
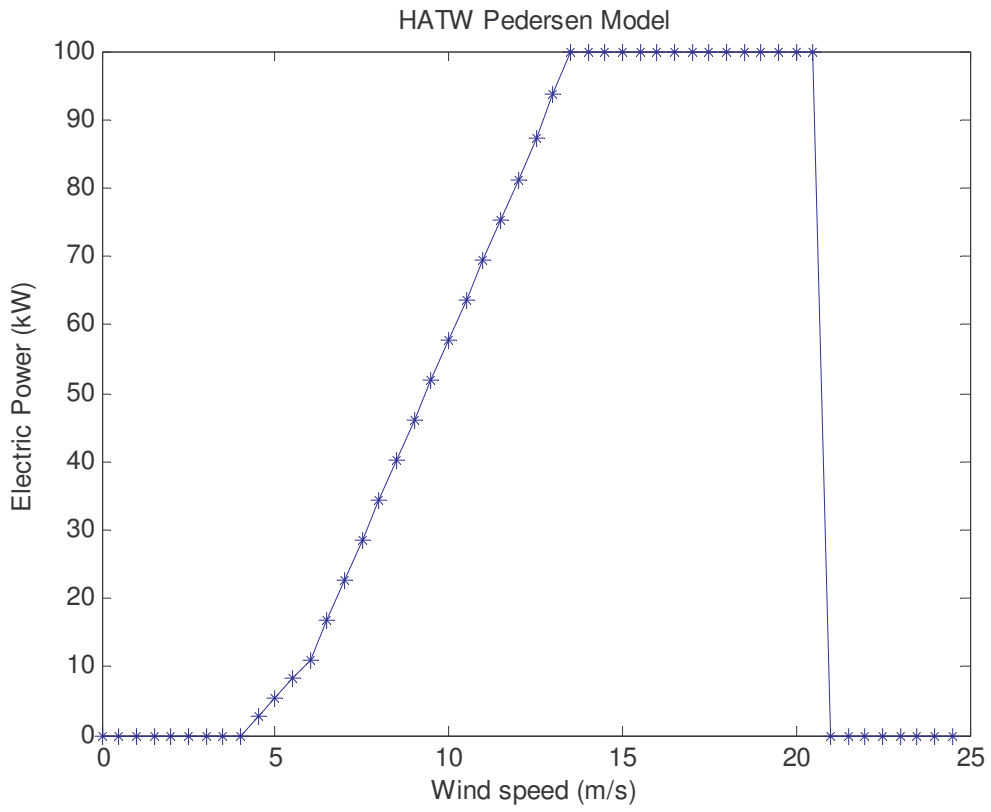


Figure 2: Exergy efficiency for PV cell (Joshi’s model): global solar radiation effect

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Figure 3: Electric power versus wind speed for HATW (Pedersen's model)

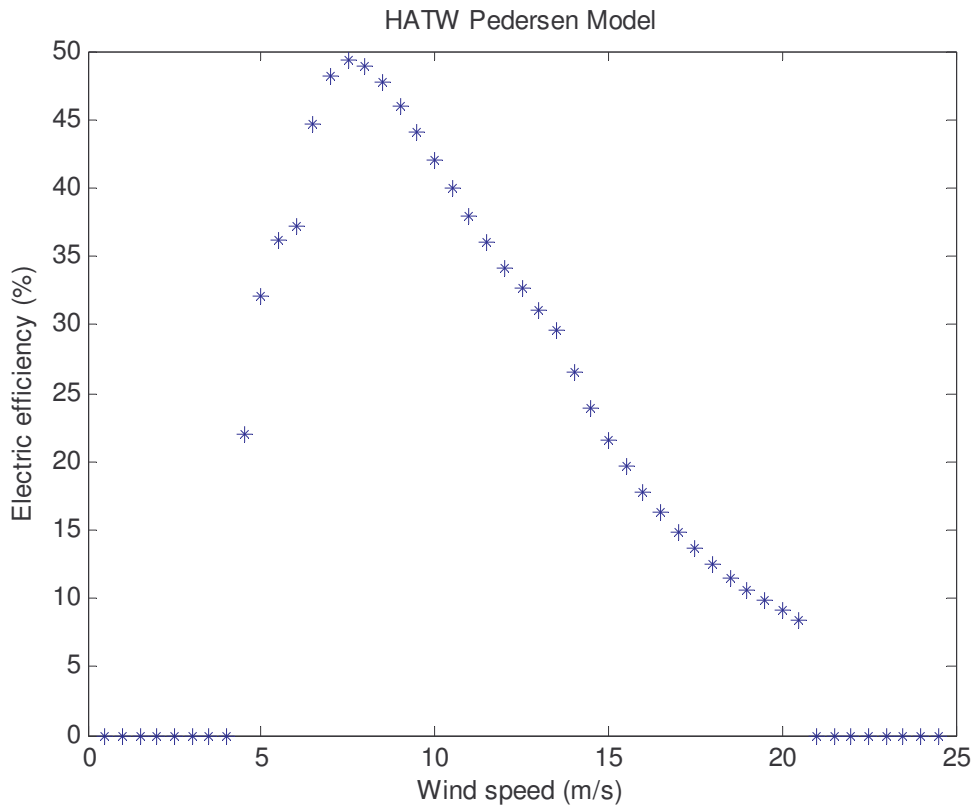
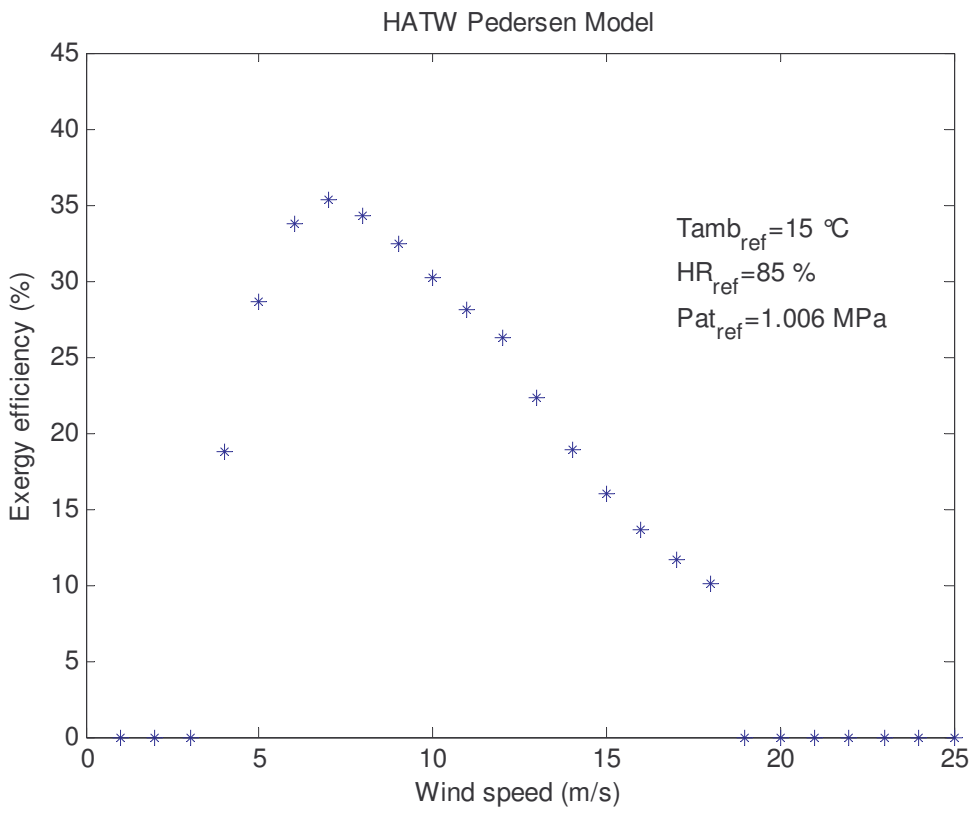


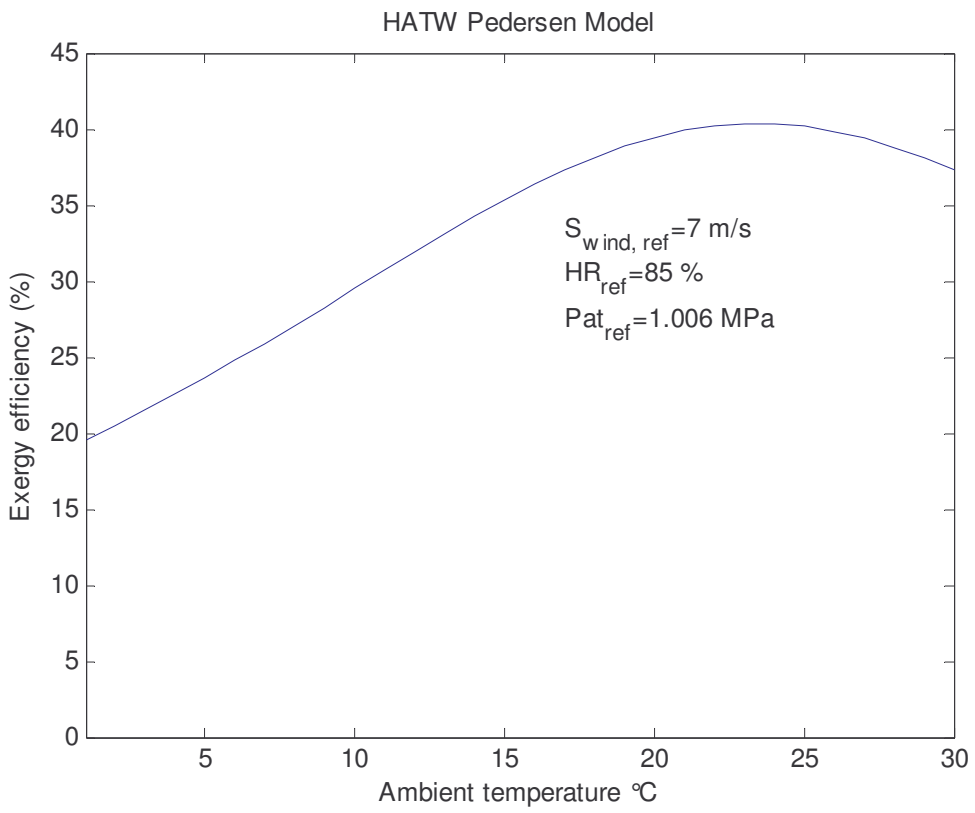
Figure 4: Electric efficiency for HATW (Pedersen's model)

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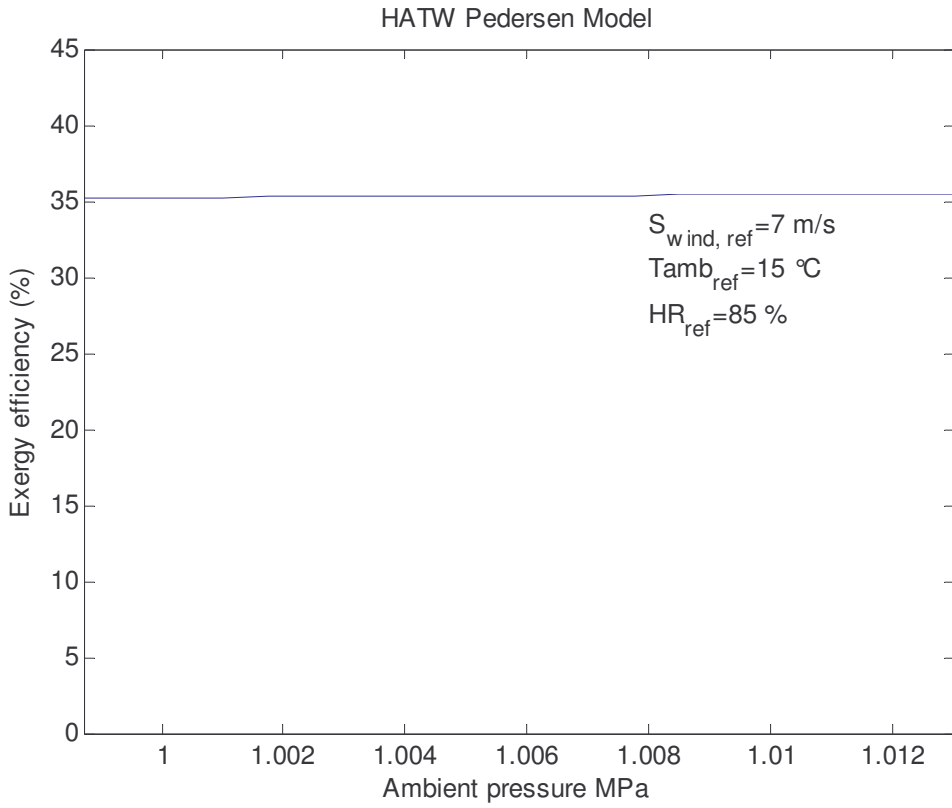
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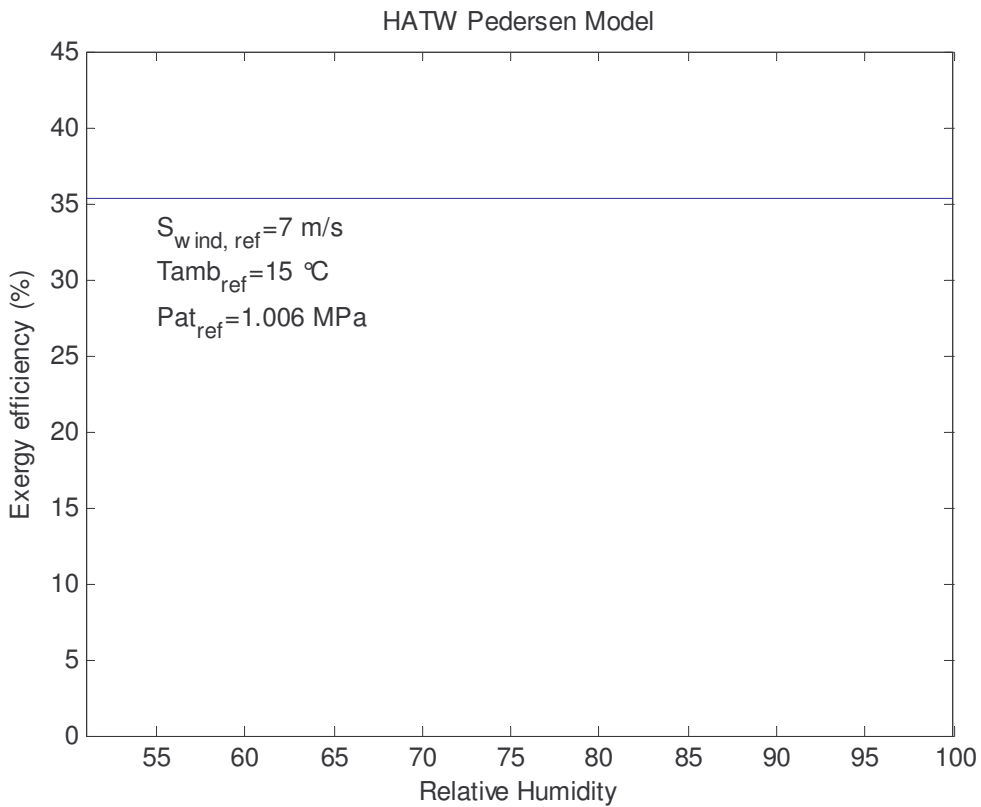
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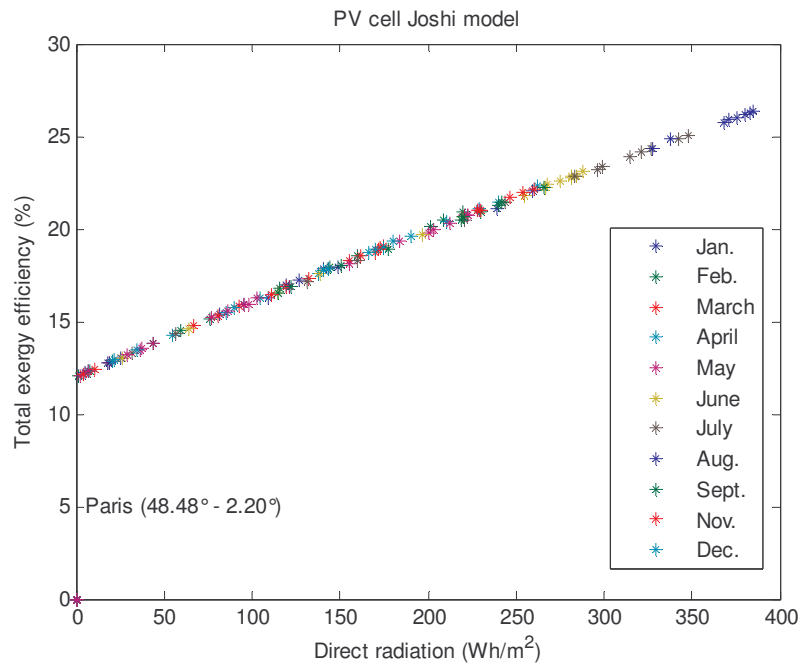
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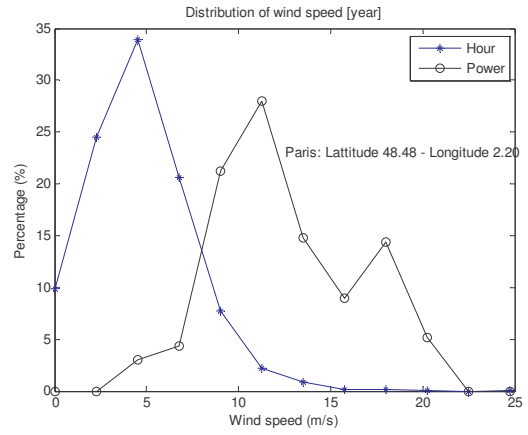
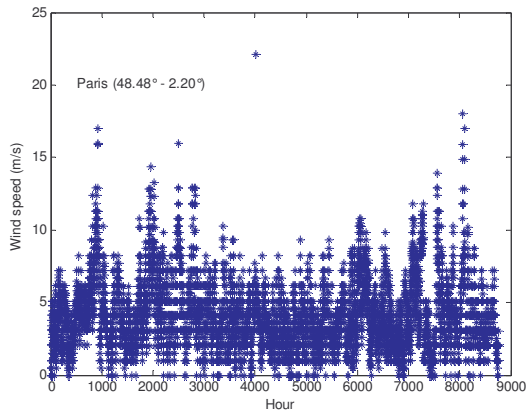
Figure 5 : Exergy efficiency for HATW (Pedersen's model): a) wind speed effect, b) ambient temperature effect, c) ambient pressure effect, and d) relative humidity effect.

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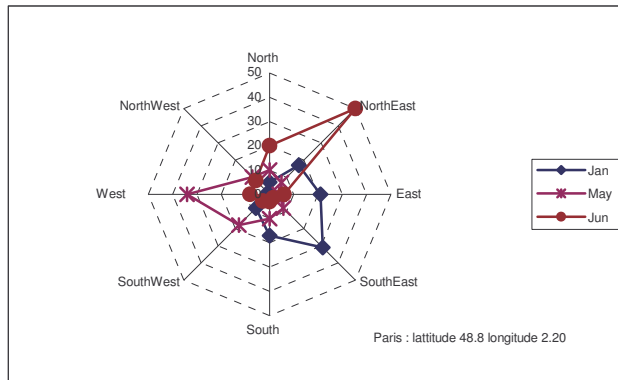


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Figure 6 : Total exergy efficiency of PV cell versus direct radiation for Paris



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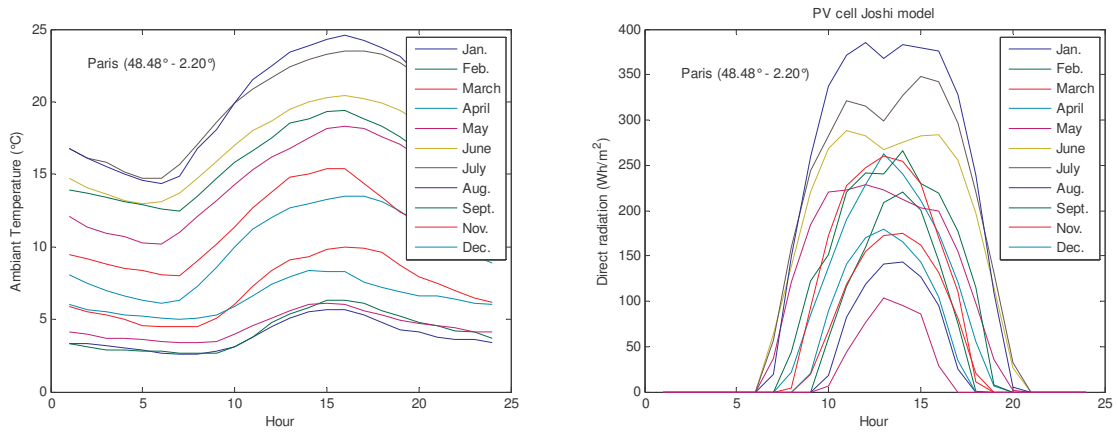
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Figure 7 : a) Representative year of wind speed for Paris
 b) Cumulative normal distribution of wind speed and its associated wind power for Paris
 c) Monthly wind direction for three months (January, May and June) for Paris

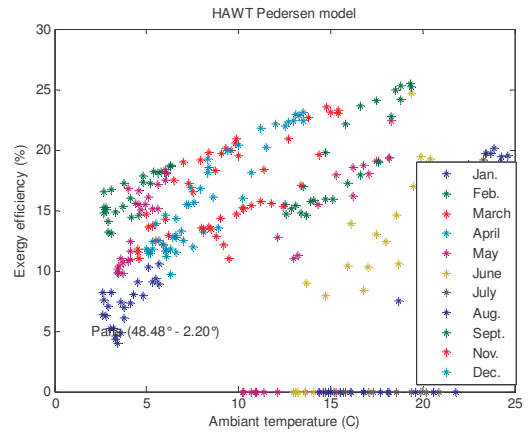
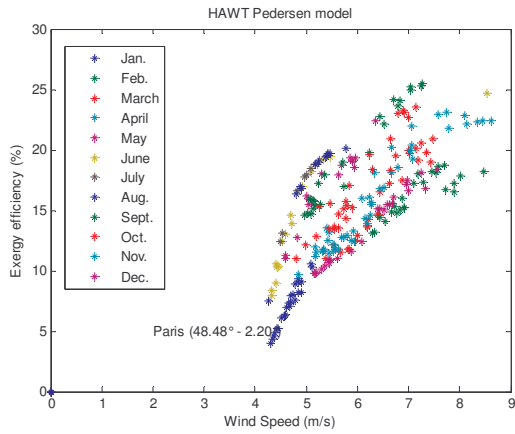
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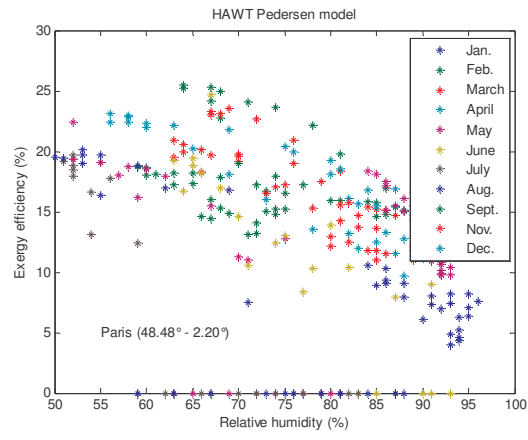
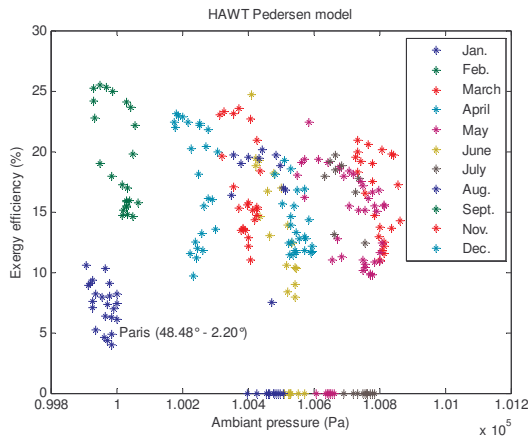
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Figure 8 : a) Monthly ambient temperature at Paris
b) Monthly direct radiation at Paris

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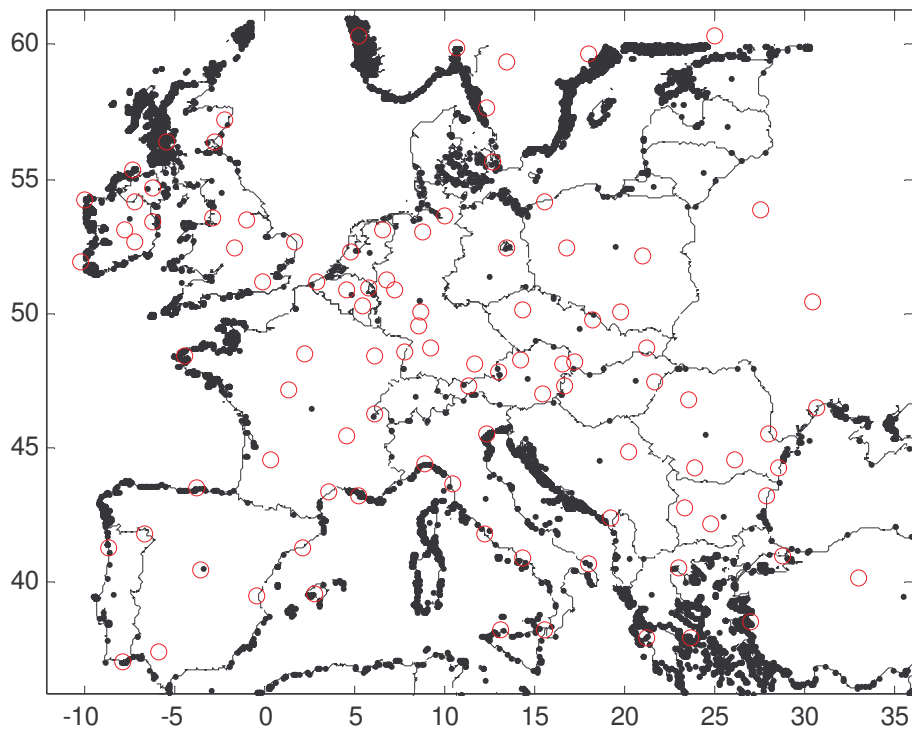
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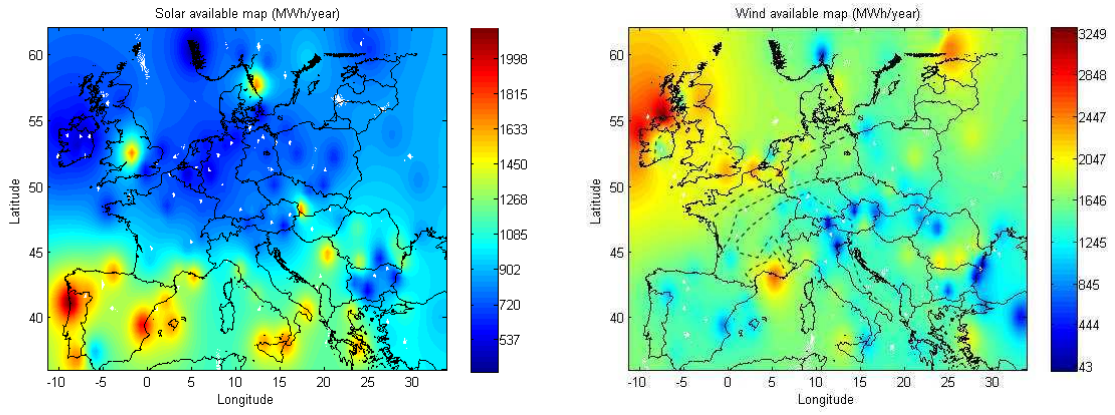
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Figure 9: Hourly exergy efficiency of HAWT
a) versus wind speed
b) versus ambient temperature
c) versus ambient pressure
d) versus relative humidity



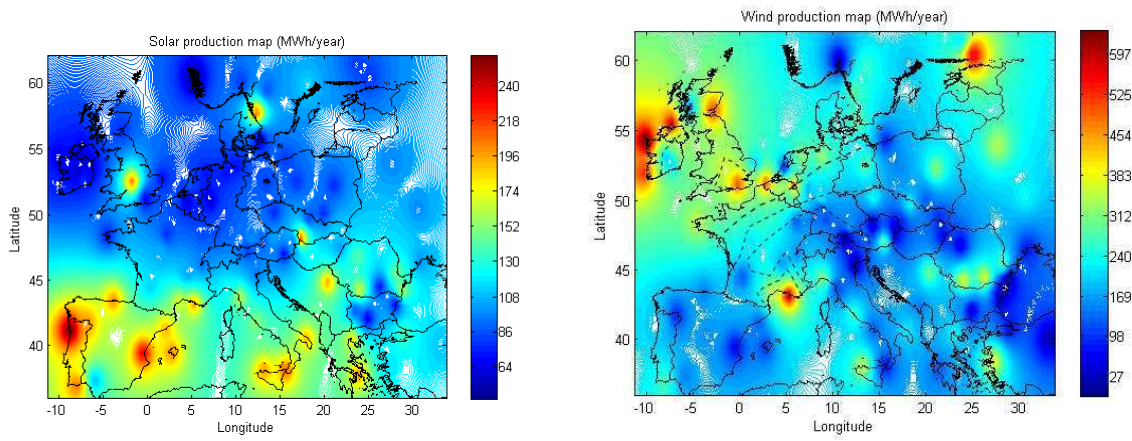
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Figure 10: Location of meteorological stations over Europe



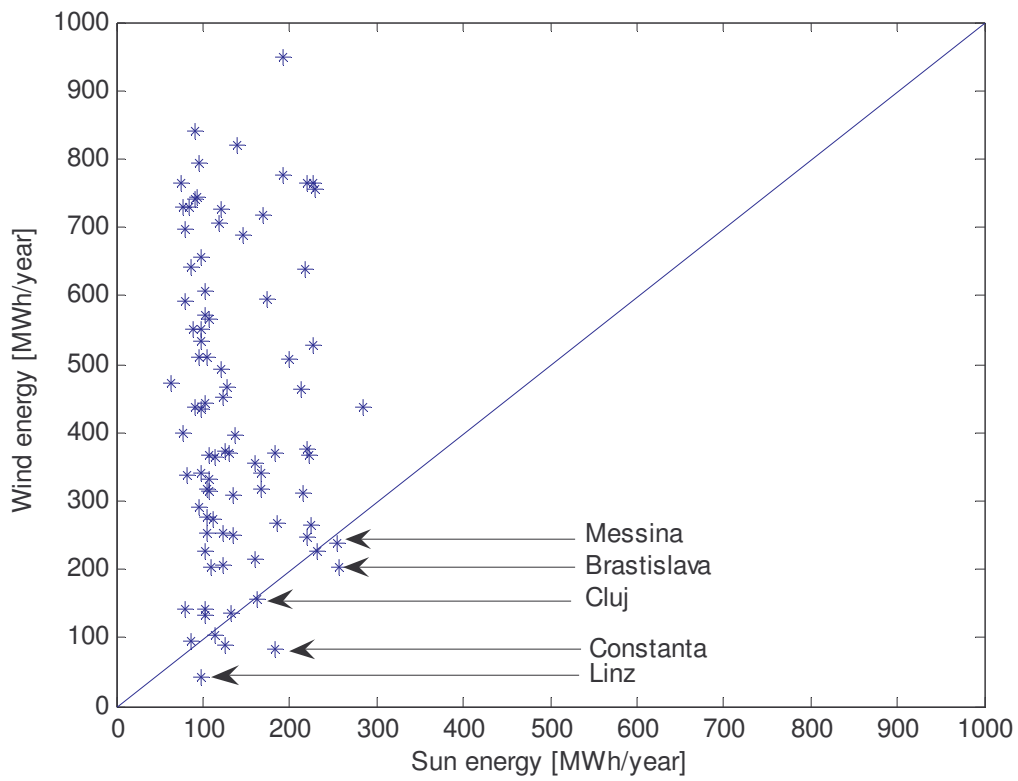
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Figure 11: Primary exergy from a) sun and b) wind resources



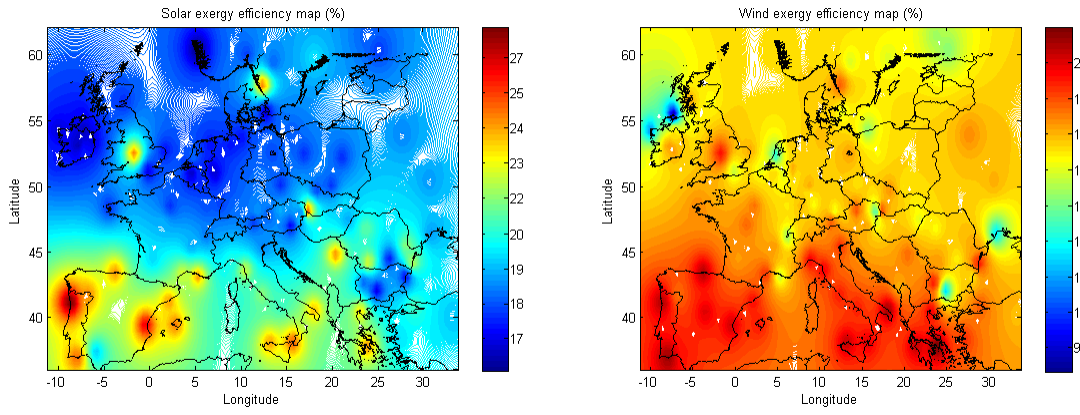
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Figure 12: Yearly electric production a) solar resource b) wind resource



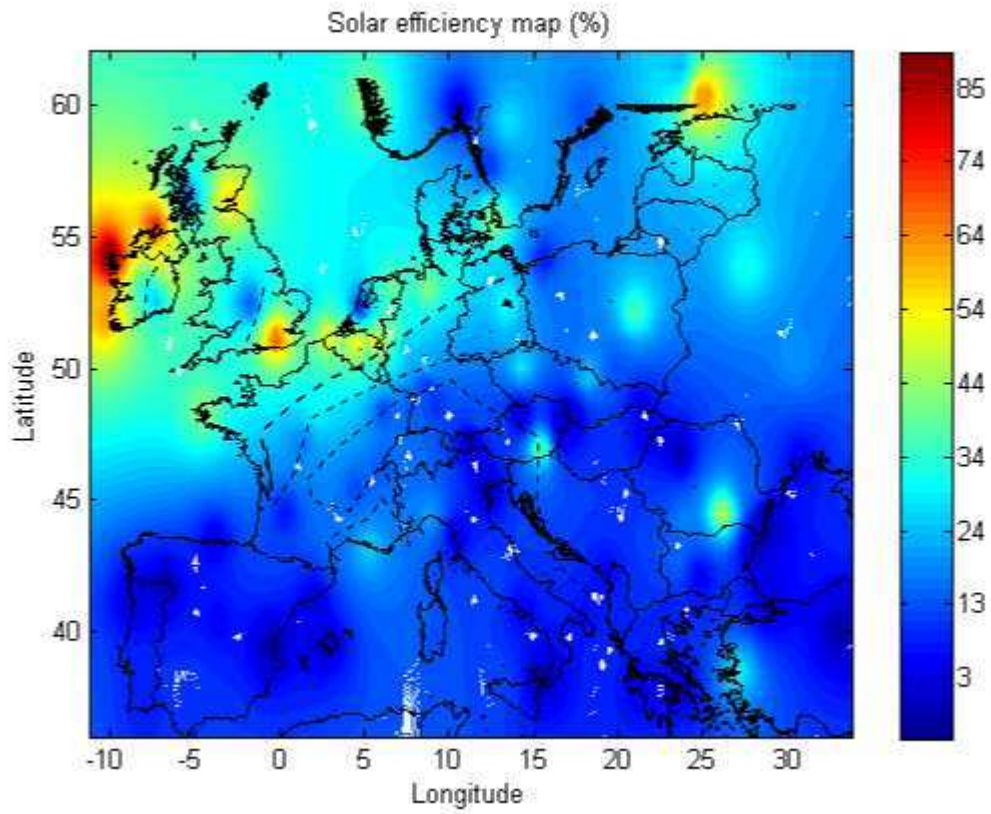
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Figure 13: Wind energy potential versus sun energy potential for the 100 meteorological stations tested



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Figure 14: Yearly exergy efficiency a) solar resource b) wind resource



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Figure 15 : Theoretical solar electric efficiency

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Table 1: Advantages/Drawbacks of wind turbines and PV cells

	Advantages	Drawbacks
Renewable Resources	Freely available do not generate direct pollution	Intermittent resources: highly climate dependent
Wind Turbines	generation and maintenance are cost effective Performances are still improving	need 3 times the amount of installed capacity to meet demand noisy construction can be very expensive may affect endangered species of birds
Photo-Voltaic cells	costs are dropping performances are improving extremely durable cheap maintenance	current technologies require large amounts of land production levels can be affected by weather conditions (for example cloudy and stormy days)

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Table 2 : Pressure and temperature variations

Wind Speed V1 [m/s]	$\Delta V=V1-V2$ [m/s]	$\Delta P=P1-P2$ [Pa]	$\Delta T=T2-T1$ wind chill [K]	HATW power [kW]
4	0.4	11.4	1.4	2.40
5	1.0	17.7	1.4	8.60
6	1.2	25.5	1.5	18.80
7	1.9	34.8	1.5	31.70
8	2.2	45.4	1.5	44.70
9	2.3	57.5	1.6	57.70
10	2.25	71.0	1.6	70.60
11	2.2	85.9	1.6	83.80
12	2.1	102.2	1.6	97.90
13	2.0	119.9	1.6	100.00

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