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Bogarino, Bruno; Kofoed, Jens Peter

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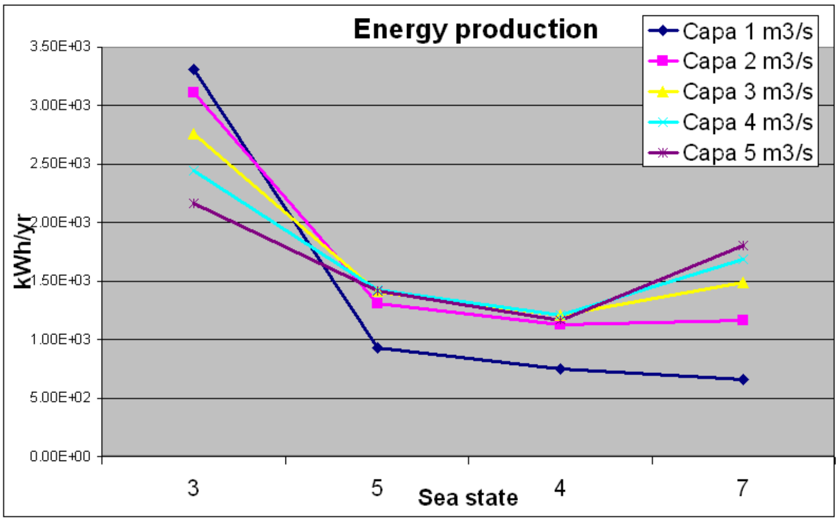

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AALBORG UNIVERSITY
Department of Civil Engineering

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Laboratory of Hydraulics and Coastal Engineering

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by

Bruno Borgarino
Jens Peter Kofoed

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List of symbols

SSG	Seawave Slot-Cone Generator
WEC	Wave Energy Converter
$EffOv$ [%]	overtopping efficiency of the reservoir
$EffRes$ [%]	reservoir efficiency, considering the spillage
g [m/s^2]	gravity
Hs [m]	significant wave height
L [m]	length of the reservoir (in the direction of wave propagation)
P_{max} [W/m]	maximal available power per meter of overtopping ramp, depending on Rc
$prob$ [-]	probability of wave occurence
P_{wave} [W/m]	available power per meter of wave crest
q [m^3/s]	overtopping water flow in the reservoir
q_{over} [m^3/s]	spill back to sea water flow
Rc[m]	crest level
Ton [m]	turbine turn on level
$Toff$ [m]	turbine turn off level
Tp [s]	peak period of the wave spectrum
W [m]	width of the overtopping ramp and of the reservoir
β [°]	wave attack angle
γ_β [-]	overtopping correction coefficient for non perpendicular waves
η_{turb} [%]	characteristic turbine efficiency
ρ [kg/m^3]	mass of water per cubic meter

Contents

Introduction

This report presents the steps carried out in order to propose a SSG setup at Liseleje location. The goal is to give an estimation of the available power and flow in the harbour. These data will assist the projects managers in their applications for funds and consents. Because the project is at its initiation phase, no economical aspects are considered in this report.

The study is based on a generic power simulation tool for overtopping based Wave Energy Converters called WOPSim (Wave Overtopping Power Simulation) [2]. This software is a generic version of the SSG simulation tool SSG2 [4]. It is an occasion of testing the enhanced version of the software for simulating the SSG structure and it provides a first experience in working with the modified tool. The study uses the previously calculated sea states at Liseleje [1], given in Section A.

1 Main issues on turbines regulation

1.1 Role of turbine regulation

The overtopping wave energy converters are generally characterized by a low head applied to the turbines. The turbine regulation aims to optimize the following points:

- Having a head in the reservoir as high as possible, in order to function with the best available turbine efficiency
- Having a water level in the reservoir low enough to avoid spill back to sea
- Limit the number of turbines cycles, to reduces the losses due to the acceleration and deceleration phases of the turbines

These different aspects are competitive, and the best compromise has to be found.

The turbines regulation is mainly determined by two values: the "Turn on level" (Ton) and the "Turn off level" ($Toff$). They represent the water levels in the reservoir for which the turbine starts or stops. The simulation program let also the user fix these levels as a linear function of the significant wave height. Obviously, the number of turbines and their characteristics play an important role in the regulation. Parameters can be set up to simulate the start-up and shutdown turbines losses.

The software which has been used permits to investigate many parameters concerning the regulation:

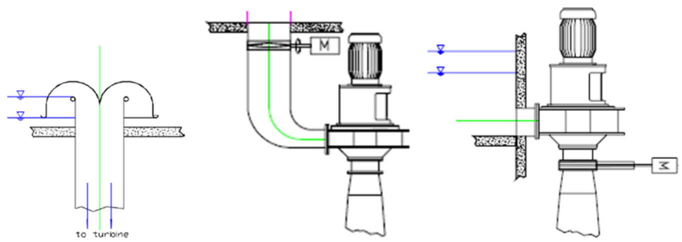
- Number of turbines
- Characteristic curves for each turbine
- Turn on and turn off levels for each turbine
- Offset and gain to express the turn on and turn off levels as linear functions of Hs
- Turbine start up and shut down times

Moreover, parameters such as the dimensions of the reservoir or the way of representing overtopping are part of input data for the regulation.

1.2 Technical regulation strategies

Several solutions for regulating the flow from the overtopping reservoir to the turbine(s) are currently studied for the pilot plant of the SSG [3]. The turbine regulation strategy depends on these technical considerations.

In order to limit the number of moving parts of the device, one solution would be to have a siphon inlet: the geometry of the siphon defines the turn on level and the turn off level. This way, it is not possible to adapt this part of the turbine strategy to the sea state, since it is fixed in the geometrical design. The other solutions are a butterfly vane, a knife gate or a cylinder gate (as on the Wave Dragon). They have moving part and need the measure of the water level in the reservoir (and in some cases of Hs) to ensure the regulation. This way, the device is more able to adapt to the sea state, but need more maintenance. At the Liseleje location, which is an easily accessible site, maintenance is not supposed to be the main constraint.



(a) Siphon inlet (b) Butterfly valve (c) Knife gate

Figure 1: Turbines regulation devices

2 Optimization at Liseleje location

2.1 Global design – geometrical breakwater constraints

The device be integrated in the breakwater of the future Liseleje marina. The following dimensions have been chosen: a width (facing the waves) of 10 m, and a length of 5 m. The storage capacity is small and can trigger problems in designing the turbines layout. The tidals effects have not been considered.

The design of the harbour shows that the main breakwater is planned to face in average the most energetic direction, which is logical. As this breakwater has a curved shape, there is still a possibility of chosing the direction of the device which needs to be investigated.

2.2 Choice of the sea states and of the adapted crest level

The device to be installed at Liseleje will be bottom fixed. It will be unable to turn to face the prevailing sea conditions. The choice of the sea states is consequently linked to the choice of the direction.

2.2.1 Direction and crest level optimization

Because of the very low sea states, it has been decided to carry out the optimization with only one reservoir. The overtopping model used in the software will be the "reference single level". The crest level has a double influence on the energy which can be extracted:

- The volume of water which overtops depends on the crest level
- The maximal head applied to the turbines is equal to the crest level

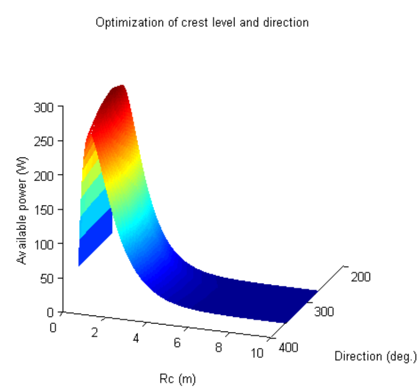
A Matlab model is used to find the optimal crest level. The maximal available power per meter of overtopping ramp can be expressed as in (1):

$$P_{max} = \rho g.q(Rc, Hs).Rc \tag{1}$$

This formula shows the conversion of the wave energy in potential energy by overtopping. The routine Matlab tests all the values of Rc on a certain range and then looks for the one maximizing P_{max}. The routine has been enriched in order to take the wave attack angle into account and work with several sea states, depending on the probability of each one. The incoming file has the format described in Figure 2 on page 3.

```
Hs      Prob        Direction
0.5,    0.79874,    360
0.5,    1.0022,     360
1,      2.37836,    360
1.5,    0.070483,   360
2,      0.31941,    360
2.5,    0.3458611,  360
3,      0.033262,   360
0.5,    0.80877,    270
0.5,    10.3057,    270
1,      4.86351,    270
1.5,    1.99692,    270
0.5,    1.6009,     300
0.5,    1.9373,     300
1,      2.5861,     300
1.5,    1.1557,     300
2,      0.39656,    300
2.5,    0.79743,    300
0.5,    1.503,      330
0.5,    1.4531,     330
1,      1.5006,     330
1.5,    0.5187,     330
1.5,    0.15329,    330
2.5,    0.254615,   330
```

(a) Liseleje sea states formatted for the routine crest level optimisation



(b) Available power (W/m) depending on the crest level and the direction

Figure 2: Use of the routine for crest level optimization

For each sea states, the power overtopping the ramp is given by (1). The routine calculates the average power by adding these powers weighted by the sea states probabilities. The influence of the direction is taken into account in the overtopping expression as follows:

- every direction between the minimum and the maximum values of the last column are tested and the incidence β is calculated
- for each direction, the correction parameter γ_β (describing the negative influence on overtopping of non-perpendicular waves) is computed and integrated in the overtopping expression.

Consequently the routine can return the direction and crest level maximizing the power. Figure 2 on page 3 shows the shape of the results. The privileged directions 0°, 270°, 300° and 330° have been chosen. These sea states directions have a wave climate of 760 W/m, which is 95% of the incident wave energy. The optimal direction and crest level define a device facing 300° with $Rc = 0.6\,m$.

2.2.2 Equivalent one direction sea states

Because working on several directions is unconvenient and time consuming, it has been chosen to continue the study with equivalent one direction sea states. These sea states, with a zero degree incidence, should give the same overtopping flow that the sum of the sea states from every direction. This solution has several advantages and disadvantages:

- - These equivalent sea states are strongly dependent on the crest level, the depth and the draft of the device. These parameters can't be modified once these sea states are fixed.
- - The procedure to find these equivalent sea states is long and fastidious
- + For the main simulation software the incidence is a parameter applying to all the sea states. To have the same results than with the equivalent sea states, it would be necessary to modify again the software or make one simulation per direction and then sum by hand the results on each sea state.
- + This way of doing considerably reduces the number of sea states to study, by summing then depending on Hs. The turbine optimization will be simplified and rationalized.

Consequently, it has been chosen to carry on this optimization with these equivalent sea states. They are obtained using the following steps (see Table 1 on page 5):

- With the main software, the overtopping flow depending on Rc is calculated for each sea state (defined by Hs, Tp, probability equal to 1, wave attack angle β).
- For each couple (Hs, Tp), the average overtopping flow $q_{av-in}(Hs, Tp)$ is calculated using the probabilities of occurrence.
- A new equivalent Hs is searched in order to reach $q_{av-in}(Hs, Tp)$ with a wave attack angle equal to zero. This way the sea states defined by the same (Hs, Tp) in several directions are concentrated in only one direction.

Table 1 on page 5 gives the final equivalent sea states, for which $Qin\,av$ is given in cubic meter for the 10 meters ramp. The sea states underlined in yellow concentrate 87% of the energy.

2.3 Influence of the turbine capacity

The total turbine capacity has been investigated by testing turbines of different sizes (from 1 m^3/s to 5 m^3/s) for the 4 most energetic operating sea states, contributing to most of the power production. The turbine turn on and turn off levels have been adjusted in order to maximize the energy production. The start-up and shutdown losses have been simulated by a start-up time and a shutdown time of 2 seconds. The turbines do not produce during the start-up time. These data are inspired by experience in designing the SSG prototype at Kvitsov location.

(a) Research of the sea states

	Tp (s)	4	4	6
	Hs (m)	0,5	1,5	1,5
0°	Prob (%)	1,00		0,07
	Qin (m3/s/m)	4,45E-03		2,87E-01
270°	Prob	10,31		2,00
	Qin (m3/s/m)	6,82E-03		3,30E-01
300°	Prob	1,94	1,16	
	Qin (m3/s/m)	9,61E-03	3,70E-01	
330°	Prob	1,45	0,52	0,15
	Qin (m3/s/m)	6,82E-03	3,30E-01	3,30E-01
	Prob	14,70	1,67	2,22
	Qav_in (m3/s/m)	7,02E-03	3,58E-01	3,29E-01
	Hs equivalent (m)	0,467	1,478	1,425
	Qsoftware (m3/s/m)	7,01E-03	3,58E-01	3,29E-01

(b) Final results

Sea state	Hs equivalent (m)	Tp (s)	Prob	Qav_in (m3/s)
1	0,472	2	0,047	0,07
2	0,467	4	0,147	0,07
3	0,946	4	0,113	1,09
4	1,478	4	0,017	3,58
5	1,425	6	0,022	3,29
6	1,922	6	0,007	6,33
7	2,436	6	0,014	10,13
8	2,797	6	0,0003	13,12

Table 1: Equivalent sea states

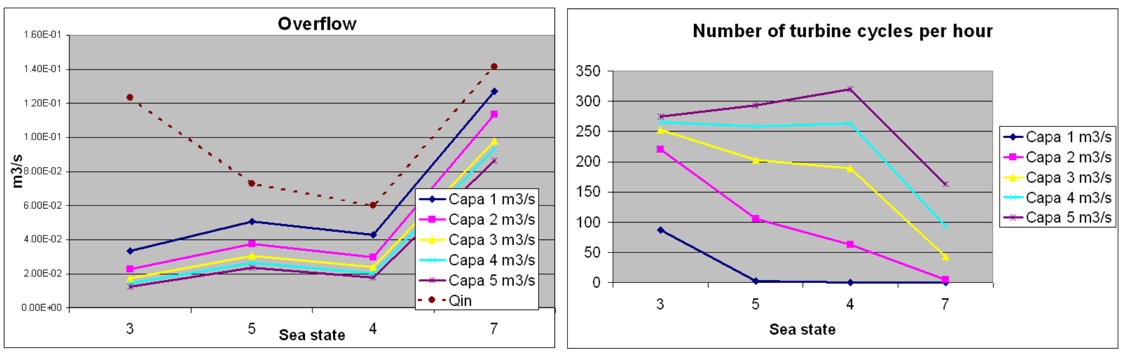


Figure 3: Influence of the turbine capacity (1)

The optimisation is computed with an overtopping time distribution on each wave period based on an exponential sine expression.

The results show a strong interaction between turbine capacity and start-up and shutdown losses (see Figure 3 on page 5 and Figure 4 on page 6).

- The number of turbine cycles is less important for the highest sea states (the water level in the reservoir do not change because of a high flow), which is reducing the start-up/shutdown losses.
- When increasing the capacity, the losses get more important for low sea states. Consequently, most of the energy in case of high capacity is produced for the highest sea states. Figure 4 on page 6 shows a transfer of the production from low to high sea states when the turbine get larger.
- A high turbine capacity reduces the spillage losses. However, from a certain point, the cycles losses triggered by the high capacity are more important than the energy gained by avoiding spillage.

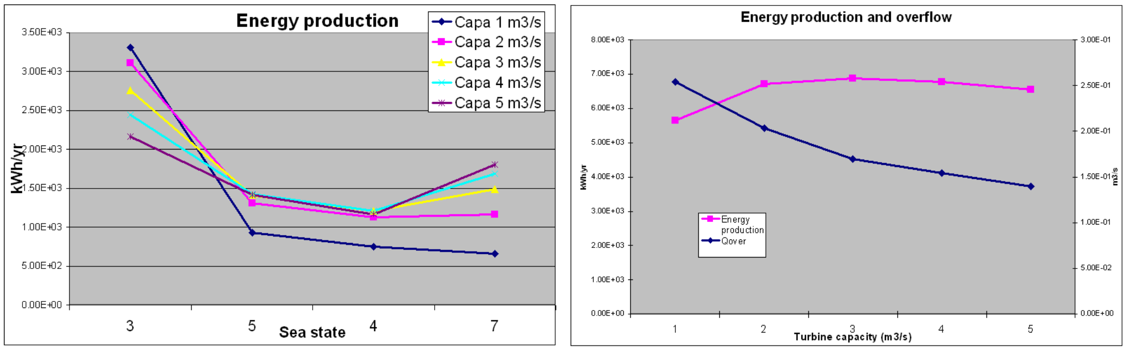


Figure 4: Influence of the turbine capacity (2)

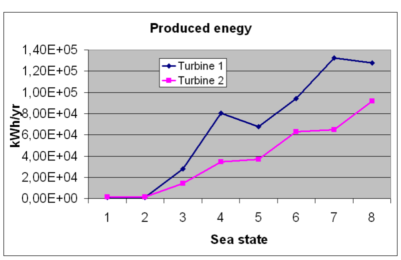
2.4 Two turbines solution

Figure 4 on page 6 shows that the turbine capacity can be adapted to the sea state in order to maximize the energy extracted from high and low sea states. Moreover, the two most energetic sea states (4 and 7) have very different overtopping flows. Consequently, it has been chosen to work with two different standard Kaplan turbines. They have as optimal flows 3 m^3/s (turbine 2) and 7 m^3/s (turbine 1). The choice of the turbine strategy should let to combine these flows to fit the climate as best as possible. The sum of the chosen turbine capacities fits with the highest overtopping discharge (sea state 7).

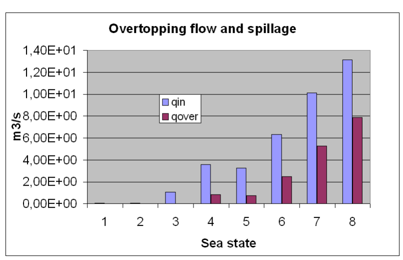
The installed power is consequently 9 220 W/meter of wave crest, for an average wave climate of 760 W/m with a maximum representative sea state of 16 030 W/m. The influence of the turbine cycles has been investigated.

2.4.1 No losses

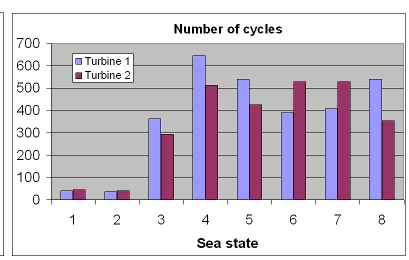
The turn on and turn off levels have been manually adjusted in order to reach the highest power production. Each sea state has been optimized separately, then the results have been summed. The final result showed an overall efficiency on energy production of 20.4%. This very high value is mainly due to the fact that losses have been neglected. Moreover, it appeared during optimization that the mean water level defined in the tank by the final turn on and turn off levels fits with the optimal turbine head. The turbines work with their higher efficiencies.



(a) Produced energy



(b) Overtopping and spill back to sea flows



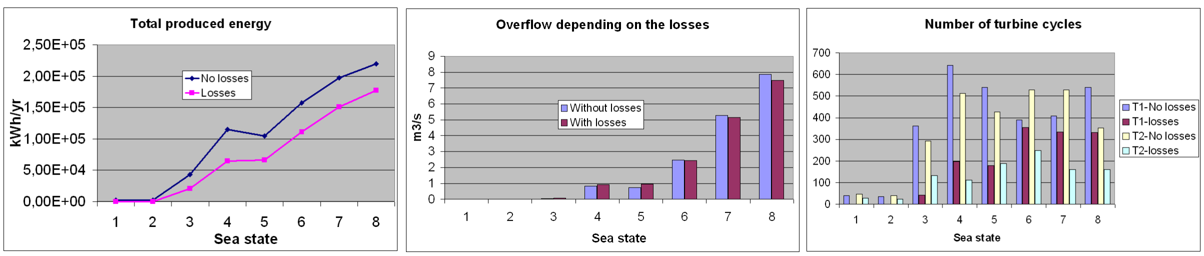
(c) Number of turbine cycles per hour

Figure 5: Optimization results (no start-up and shutdown losses)

Consequently such an optimization is not really reliable because it only moves the water level to the most convenient level, no matter the spillage. However the choice of the quite high turbines capacities results in a reasonnably small spillage, even for the highest sea states. The two turbines have approximately the same turn on and turn off levels; consequently Turbine 1 produces more. The number of turbine cycles has no energy cost in these tests, so it is very large and physically senseless. The small storage capacity ($L = 5\,m$) is also responsible of these high values, because the water level has to oscillate rapidly.

2.4.2 Start-up and shutdown losses included

As a first step, the previous turbines levels have been kept and the losses have been applied. It triggered dramatically large energy losses, the overall efficiency dropping from 20.4% to 8.7%. This certainly shows a too high turbine capacity. By adjusting manually the turbines levels, it has been possible to increase this efficiency until 11.9%. Figure 6 on page 7 compares the last results with the previous simulations. It can be seen that the spill back to sea slightly decreases for the highest sea states. However, energy is mainly gained by diminishing the number of turbine cycles. Because of a low reservoir storage capacity, this number remains large.



(a) Produced energy (b) Spill back to sea flow (c) Number of cycles per hour

Figure 6: Production results without and with losses

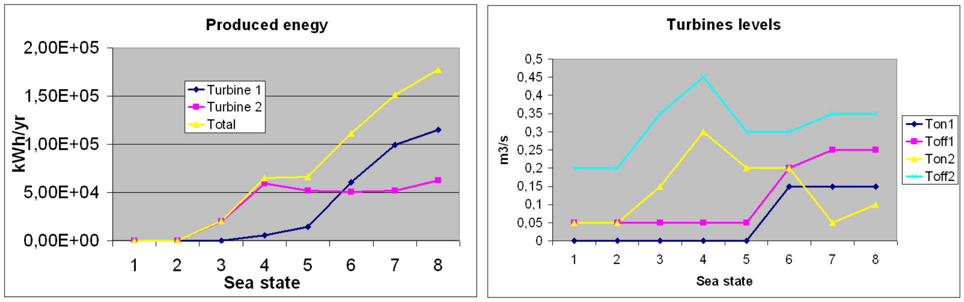
Figure 7 on page 8 shows the final turbines levels for each sea state and the energy production per turbine. It can be seen that the turbines finally play the expected role, depending on their capacities:

- For the low sea states Turbine 1 (higher capacity) is used only in the higher area of the reservoir, to limit the spill back to sea. Turbine 2 is used for the rest of the work span, in order to keep a higher head in average.
- For the high sea states, when a large capacity is necessary, the work span is defined by the levels of Turbine 1. Turbine 2 helps to keep the water level low enough to reduce spillage losses.

This behaviour explains the shape of the energy production of Turbine 2. It is clear that from sea state 4, the turbines exchange their roles.

The software let fix the turn off and the turn on levels of the turbine as linear functions of Hs. Two different regulations have been tested:

- Mechanical regulation: the regulation device is supposed to be a siphon inlet, with no moving parts. Consequently, the levels will not be able to adapt to a measured Hs. Ton and $Toff$ are the average of Ton and $Toff$ for each sea state weighted by the expected energy for each sea state;



(a) Produced energy per turbine (b) Turbines levels (distance from the crest level)

Figure 7: Turbine strategy

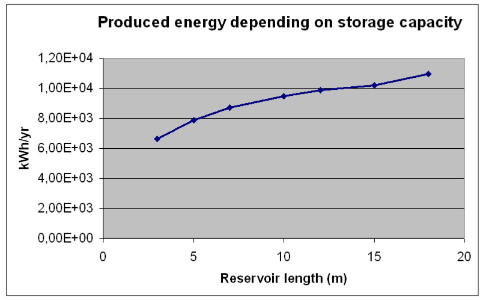
- Automatic regulation : the regulation device can be a butterfly vane or a knife gate, which automatically react to the measure of the wave height and of the pressure in the reservoir. The regulation coefficients have been chosen to fit with the 4 most energetic sea states.

Table 2 on page 8 gives the final results. Because the sea states have all been computed together, the different expressed energies are now related to the probability of the sea state. It can be seen that the choice of the regulation influence the final results. However, the gain of an automatic regulation is relatively small, because most of the incoming energy is concentrated on a few sea states. Consequently a mechanical regulation can be a cost-effective choice.

					Mechanical regulation		Automatic regulation	
Sea state	Hs (m)	Tp (s)	Prob	Incoming energy (kWh/yr)	Produced energy (kWh/yr)	Overall efficiency (%)	Produced energy (kWh/yr)	Overall efficiency (%)
1	0,472	2	0,047	8,82E+02	6,95E-01	0,08	2,22E+00	0,25
2	0,467	4	0,147	5,50E+03	1,40E+01	0,25	1,77E+01	0,32
3	0,946	4	0,113	1,70E+04	1,58E+03	9,32	2,33E+03	13,75
4	1,478	4	0,017	5,64E+03	9,79E+02	17,35	1,07E+03	18,87
5	1,425	6	0,022	1,12E+04	1,36E+03	12,12	1,43E+03	12,71
6	1,922	6	0,007	6,43E+03	7,51E+02	11,67	7,54E+02	11,71
7	2,436	6	0,014	1,96E+04	2,08E+03	10,58	2,11E+03	10,75
8	2,797	6	0,0003	6,73E+02	1,76E+02	26,14	1,78E+02	26,43
			Total	6,70E+04	6,94E+03	10,36	7,89E+03	11,78

Table 2: Final results with the two turbines solution

The final overall efficiency is quite disappointing, given how the turbine capacity have been over-designed in order to fit to very diverses sea states. It confirms that the high capacity turbine wastes a not negligible part of the energy in start-up and shutdown losses. The small storage capacity increases this tendency. Figure 2.4.2 on page 9 shows the positive influence of a larger reservoir.



(a) Reservoir length

Figure 8: Influence of the storage capacity

2.5 One turbine solution

It has been chosen to get back to the results from 2.3. The results of the levels optimization with a turbine of a 3 m^3/s capacity have been used to test a mechanical and an automatic regulation. The installed capacity is now 2700 W/m for a wave climate of 760 W/m. Table 3 on page 9 gives the final results. The following results should be underlined:

- The overall efficiency slighlty decreases from the study with two turbines. However the power output has to be compared to the installed capacity. It can be seen that the second solution is much more efficient, mainly because start-up and shutdown losses have been diminished thanks to a smaller turbine capacity.
- The total probability of the sea states covers only 37% of the time, because of the choice of high enough significant wave height and privileged directions.
- The global overtopping efficiency, deducted from the crest level optimisation, is relatively good and lets an extraction of 39.5 % of the incoming energy.

					Automatic regulation		Mechanical regulation	
Sea state	Hs (m)	Tp (s)	Prob	Incoming energy (kWh/yr)	Produced energy (kWh/yr)	Overall efficiency (%)	Produced energy (kWh/yr)	Overall efficiency (%)
1	0.472	2	0.047	8.82E+02	2.53E+01	2.87	5.75E+00	0.65
2	0.467	4	0.147	5.50E+03	8.24E+01	1.50	3.69E+01	0.67
3	0.946	4	0.113	1.70E+04	2.81E+03	16.56	2.78E+03	16.37
4	1.478	4	0.017	5.64E+03	1.20E+03	21.30	1.20E+03	21.18
5	1.425	6	0.022	1.12E+04	1.41E+03	12.57	1.41E+03	12.56
6	1.922	6	0.007	6.43E+03	6.44E+02	10.01	6.27E+02	9.74
7	2.436	6	0.014	1.96E+04	1.50E+03	7.64	1.45E+03	7.41
8	2.797	6	0.0003	6.73E+02	1.14E+02	16.98	1.11E+02	16.52
			Total	6.70E+04	7.79E+03	11.63	7.62E+03	11.38

Table 3: Final results with the one turbine solution

The results with the automatic regulation are the following: the final energy production is 7.79 MWh/year, which is an overall efficiency of 11.6%. The comparison of the overall efficiency with the optimal layout of the Kvistov pilot plant shows that it is a reasonnable value. The overflow can be collected in order to create a current in the harbour. The total flow will be the sum of:

- The flow through the turbines: 0.291 m^3/s in average.
- The overflow: 0.215 m^3/s in average.

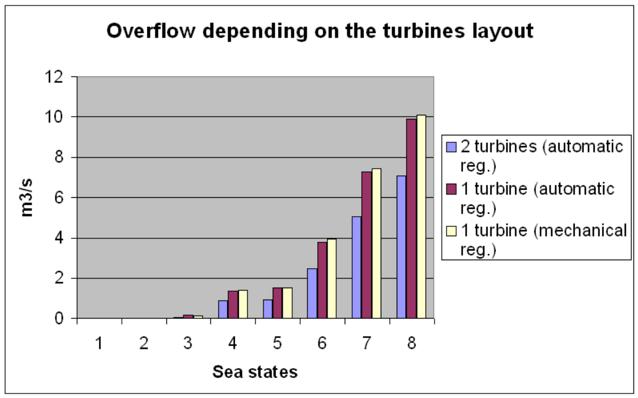


Figure 9: Overflow depending on the turbines layout

It means a yearly volume of 15.9 millions of cubic meters. Finally, even if the overflow is much more important with the second solution (see Figure 9 on page 10), the power production is approximately the same. That means that the turbine is better used. The overflow in not a loss, given that it can create a current in the harbour with a higher speed that the flow expelled from the turbines.

3 Observations about WOPSim

Experience in using the software revealed that some new precautions are necessary.

- Number of turbine cycles per hour: there is at least one cycle per sea state, and this number cannot be devided. When working with very small probabilities, as is this study, the final number of cycles is dramatically overestimated when the software makes to final average. Consequently this parameter has to been studied with each sea state separately, with a probability of 1.
- Zero energy sea states: in order to work with a total probability of 1, a ninth sea state has been used here, supposed not to produce any energy ($Hs = 0.01\,m$, $Tp = 0.01\,s$). However the initial freespace fixes an initial water level inte the reservoir: it is an amount of potential energy which is converted by the turbine. Consequently, this last sea state has to be computed on a large number of waves, in order to have a low average power and energy production. Tests with one wave show that the production for this sea state can be dramatically large otherwise.

Conclusion

This report has presented a method to use the production simulation software. Optimization can be simplified by using equivalent sea states, collapsing the wave climate on the main incidence direction.

A large range of turbine capacities has been tested. The results show that the start-up/shutdown losses can have a dramatic effect in case of high turbine capacity. The choice of a smaller capacity let the turbine work better (less starts and stops) and reduces the installing cost, the final power production being equal. The overflow can be converted in a current in the harbour, increasing the global efficiency of the system.

Final results give an idea of the yearly power production and flow in the harbor of Liseleje. Optimal levels for the turbine regulation (see Section B) should permit to maximize the power output. From this, economical studies are still necessary in order to make the project cost effective.

References

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A Wave conditions at Liseleje location

	Tp (s)	**2**	**4**	**4**	**4**	**6**	**6**	**6**	**6**	**6**	**6**		
	Hm0 (m)	**0,5**	**0,5**	**1**	**1,5**	**0,5**	**1**	**1,5**	**2**	**2,5**	**3**	**Sum**	**%**
0°	Prob (%)	0,80	1,00	2,38				0,07	0,32	0,35	0,03	4,95	4,95
	Power (W/m)	214	427	1 710				5 771	10 260	16 031	23 084	57 497	43,60
	Power * Prob	171	428	4 067				407	3 277	5 544	768	14 662	18,13
30°	Prob (%)	0,71	2,42	0,56		2,42	0,05					6,16	6,16
	Power (W/m)	214	427	1 710		427	2 565					5 344	0,00
	Power * Prob	151	1 034	962		1 034	125					3 305	4,09
90°	Prob (%)	3,13										3,13	3,13
	Power (W/m)	214										214	0,16
	Power * Prob	668										668	0,83
240°	Prob (%)	2,14										2,14	2,14
	Power (W/m)	214										214	0,16
	Power * Prob	457										457	0,56
270°	Prob (%)	0,81	10,31	4,86				2,00				17,97	17,97
	Power (W/m)	214	427	1 710				5 771				8 122	6,16
	Power * Prob	173	4 406	8 316				11 524				24 419	30,19
300°	Prob (%)	1,60	1,94	2,59	1,16				0,40	0,80		8,47	8,47
	Power (W/m)	214	427	1 710	3 847				10 260	16 031		32 489	24,64
	Power * Prob	342	828	4 422	4 446				4 069	12 783		26 891	33,25
330°	Prob (%)	1,50	1,45	1,50	0,52			0,15		0,25		5,38	5,38
	Power (W/m)	214	427	1 710	3 847			5 771		16 031		28 000	21,23
	Power * Prob	321	621	2 566	1 996			885		4 082		10 470	12,95
											Prob (%)	48,20	48,20
											Power (W/m)	131 879	100,00
											Power * Prob	80 872	100,00

Figure 10: Near shore wave climate at Liseleje (power in W/m, probabilities in %)

B Optimal turbine layout

B.1 Turbine characteristic curves

(a) Turbine 2

H [m]	Q [m^3/s]	eta [%]
0,2	2,47	52,48
0,25	2,58	70,82
0,3	2,67	80,21
0,35	2,76	85,22
0,4	2,84	87,88
0,45	2,92	89,18
0,5	3,00	89,68
0,55	3,07	89,67
0,6	3,14	89,35

Table 4: Turbine characteristic curves

B.2 Turbines turn on and turn off levels

Sea state	Ton	Toff
3	0.15	0.2
5	0.25	0.3
4	0.25	0.3
7	0.4	0.45

Table 5: Turbine turn on and turn off levels (distance from the crest level, m)

B.3 Regulation coefficients

(a) Automatic regulation

	Gain	Offset	Lower	Higher
Ton	0.16	0.0541	0.13	0.51
Toff	0.16	0.0041	0.08	0.46

(b) Mechanical regulation

Ton	0.2
Toff	0.25

Table 6: Turbine levels (m)