PRELIMINARY TURBINE HYDRODYNAMIC DESIGN

ADVANCED TIDGEN® POWER SYSTEM
US DEPARTMENT OF ENERGY AWARD: DE-EE0007820

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Table of Contents

1 Purpose

This document is deliverable D1.1, which fulfills milestone 1.1 for the project

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Project Title:	Advanced TidGen® Power System
Prime Recipient:	ORPC Maine
Principal Investigator:	Jarlath McEntee, P.E.

The document provides the preliminary turbine hydrodynamic design, with supporting CFD analysis, hand-off to structural analysis and design description.

2 CFD Analysis

To perform preliminary Hydrodynamic Turbine Design, for the Advanced TidGen® Power System project a number of CFD tools were utilized. Preliminary turbine size was calculated using inhouse calculators that were produced using Microsoft Excel which calculated the potential energy extractable from flowing water. QBlade, a tool used to evaluate horizontal axis cross flow turbines was used to start the preliminary hydrodynamic turbine design. QBlade is a double stream tube model that has both blade element momentum (BEM) theory and the additional capability of applying lifting line free vortex wake models. Once the overall preliminary size and turbine architecture was developed, Computational Fluid Dynamic (CFD) studies were performed.

TidGen® 1.0 Turbine

A study was performed of the baseline TidGen® 1.0 turbine:

Specifications for TidGen® 1.0

- Turbine Radius – barreled from 1.3 to 1.4m with maxium radius at mid-span
- Turbine Length – 5.6m long

- Foils – Four NACA63-415, mounted at mid-chord, suction side out
- Chord – 0.356m

Three variants of the foil profile were analyzed in QBlade: a sharp trailing edge NACA63-415 profile, and two variants of a blunt trailing edge (Figure 1). Figure 2 shows the 1.0 tubine configuration with 4 twisted foils. The analysis indicated that QBlade results are insensitive to small differences in trailing edge geometry. The foil profile of the baseline TidGen® 1.0 turbine was a NACA 63-415 with a marine variant trailing edge.

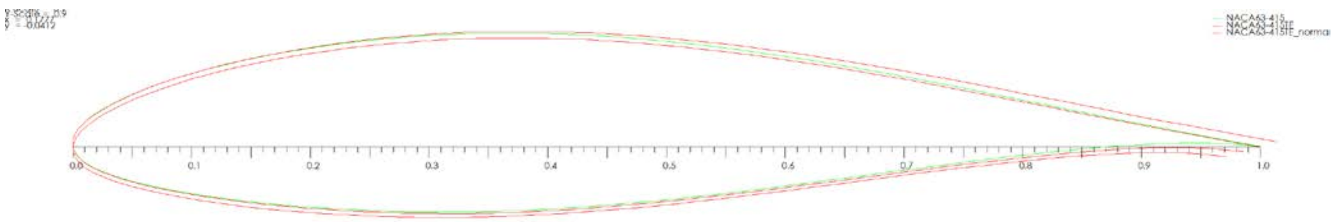

Figure 1: Non-dimensional TidGen 1.0 foil

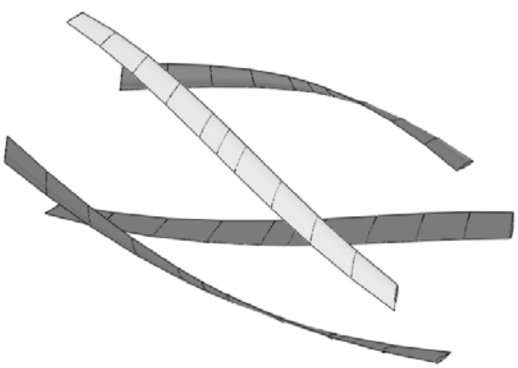

Figure 2: TidGen 1.0 Turbine

Max CP is 0.44 at a TSR of 1.9. No significant difference can be ascribed to the trailing edge treatments. Results to the right of 2.0 Tip Speed Ratio are suspect due to numerical instabilities in the QBlade modeling which appear inherent to the particular airfoil profile arrangement for TidGen® 1.0.

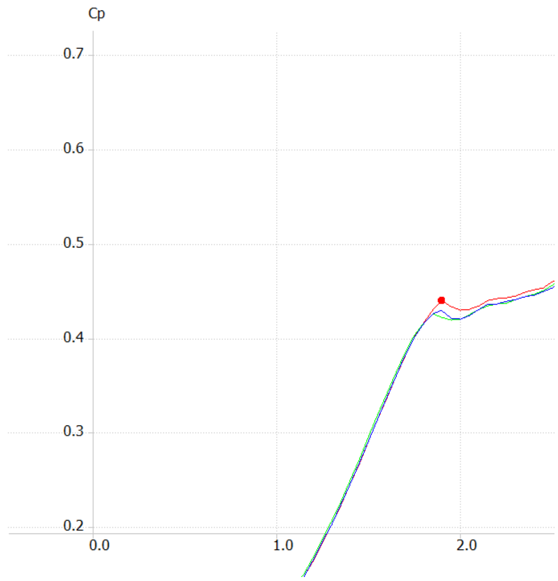

Figure 3: TidGen 1.0 baseline performance from QBlade Streamtube analysis

TidGen® 2.0 Turbine

The preliminary turbine size was calculated using inhouse Excel tools which calculated the energy extractable from flowing water. Basic theory suggests that the lower solidity ratio would result in a more efficient turbine. For this reason, the decision was made to evaluate a three-foil turbine as opposed to the four-foil turbine built for the TidGen® 1.0. In addition the barreling of the turbine was removed as this feature introduced significant manufacturing complexity to the tooling and parts. The baseline geometry of the TidGen® 2.0 system was changed to

- Turbine Radius – straight – 1.1m
- Turbine Length – 6.25m long
- Foils – Three NACA mpxx four-digit series mounted at mid-chord
- Chord – 0.3m

QBlade Streamtube Analysis

In QBlade, NACA four digit airfoils were analyzed by varying different parameters until the optimum foil profile of a NACA 1520 with a chord length of 0.3 meters and the suction side facing in towards the turbine shaft was determined. A series of runs were conducted to select the best values of profile thickness and camber, as well as direction of suction side, pitch angle, and mounting location.

By a series of modeling steps an optimum turbine with a geometry of 3 foils, NACA1320, with a -3 degree pitch was arrived at. By a completely separate and parallel effort a different turbine configuration was determined to be optimum. This was a NACA1520 with a -1 degree pitch. Since the path used to arrive at the optimum may have influenced the final selection we compare these turbines directly.

Comparison shows that the 1320, -3 deg performs better than the 1520 -1 deg, but that the 1520 -3 deg is very similar to the 1320 -3 deg (Figure 4).

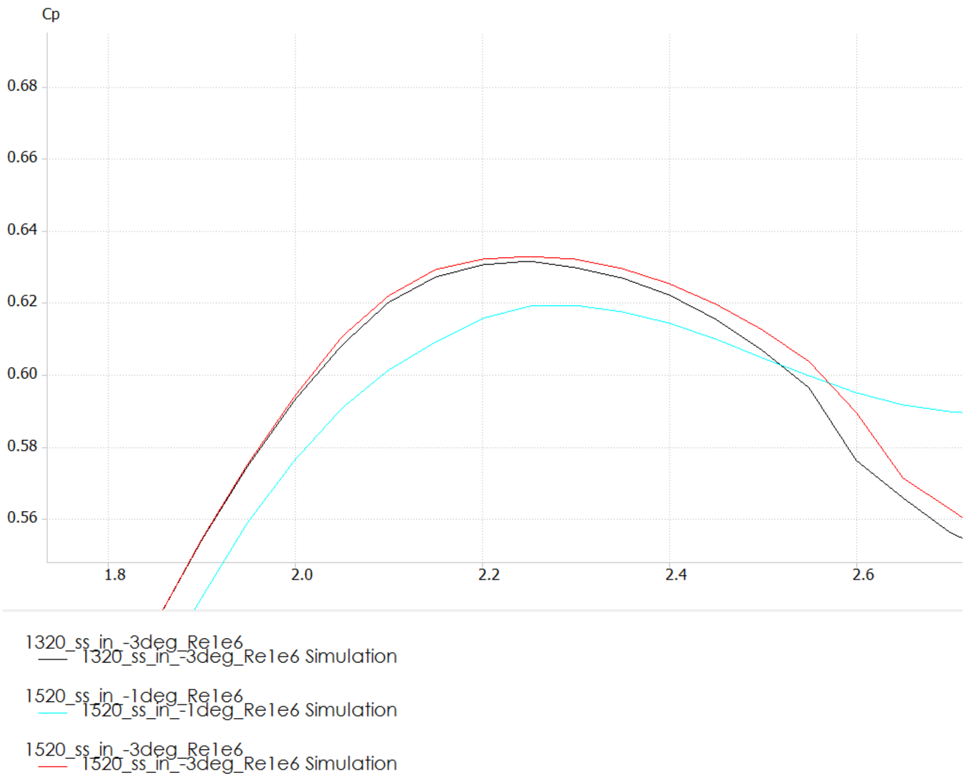

Figure 4: TidGen 2.0 study: comparison of 1320, and 1520 turbines with different pitch angles

Chord Study

For the 1320 and 1520 turbines we reduced chord from 0.3m to 0.25m, and as expected the reduction in solidity improved performance and shifted TSR and CP upwards. Reduction in chord also leads to reductions in Reynolds number which are not automatically captured in these analyses. Results for a RE = 0.5e6 are presented below (Figure 5).

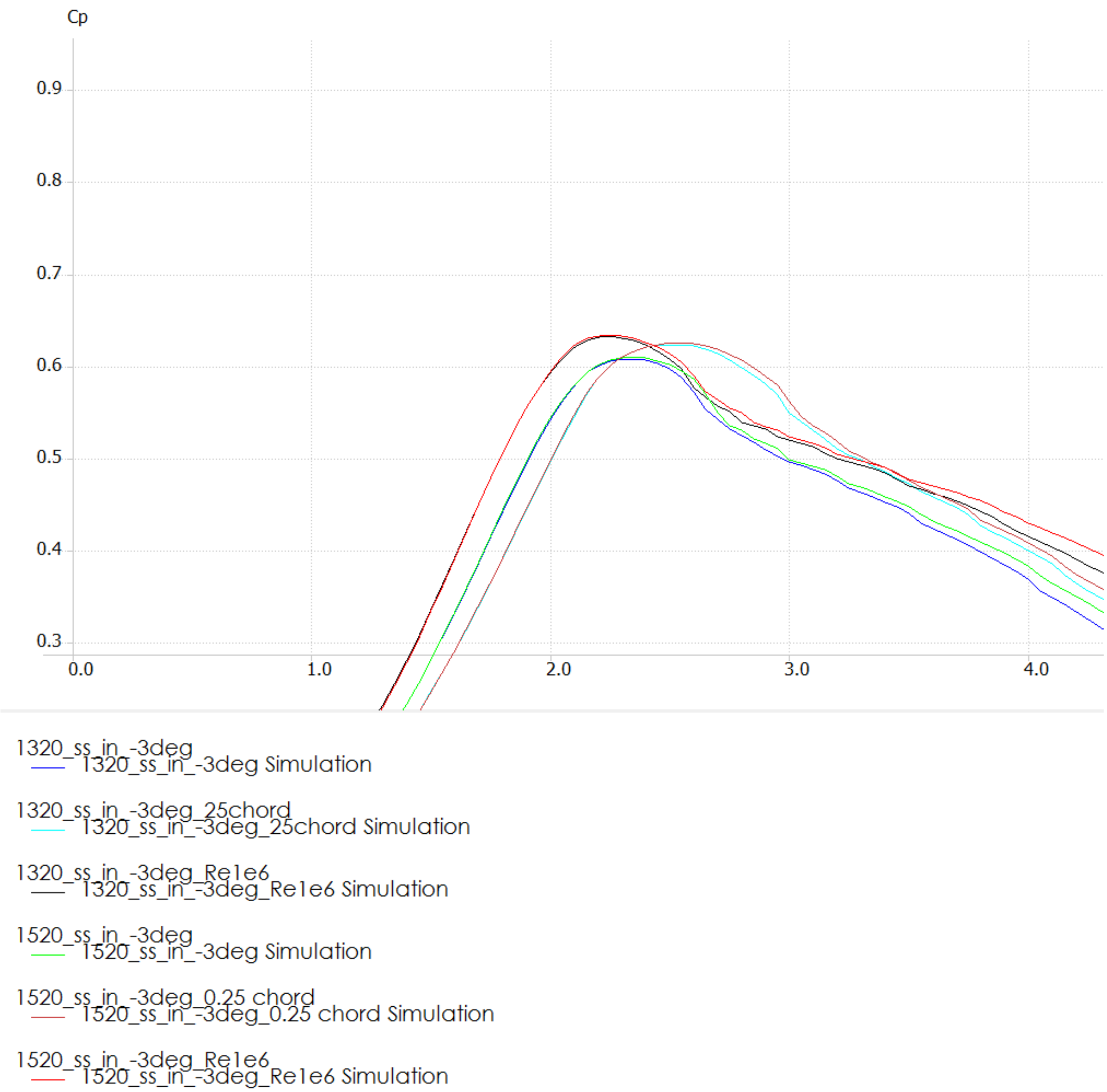

Figure 5: TidGen 2.0 study: effect of chord length on performance. Base case is 0.3m chord.

Sensitivity to Chord Study

To confirm that changes in chord do not affect the selection of the profile a series of analyses changing foil thickness, camber and pitch values was performed (Figure 6). The 1320, -3, suction side in, profile appears to be a robust selection.

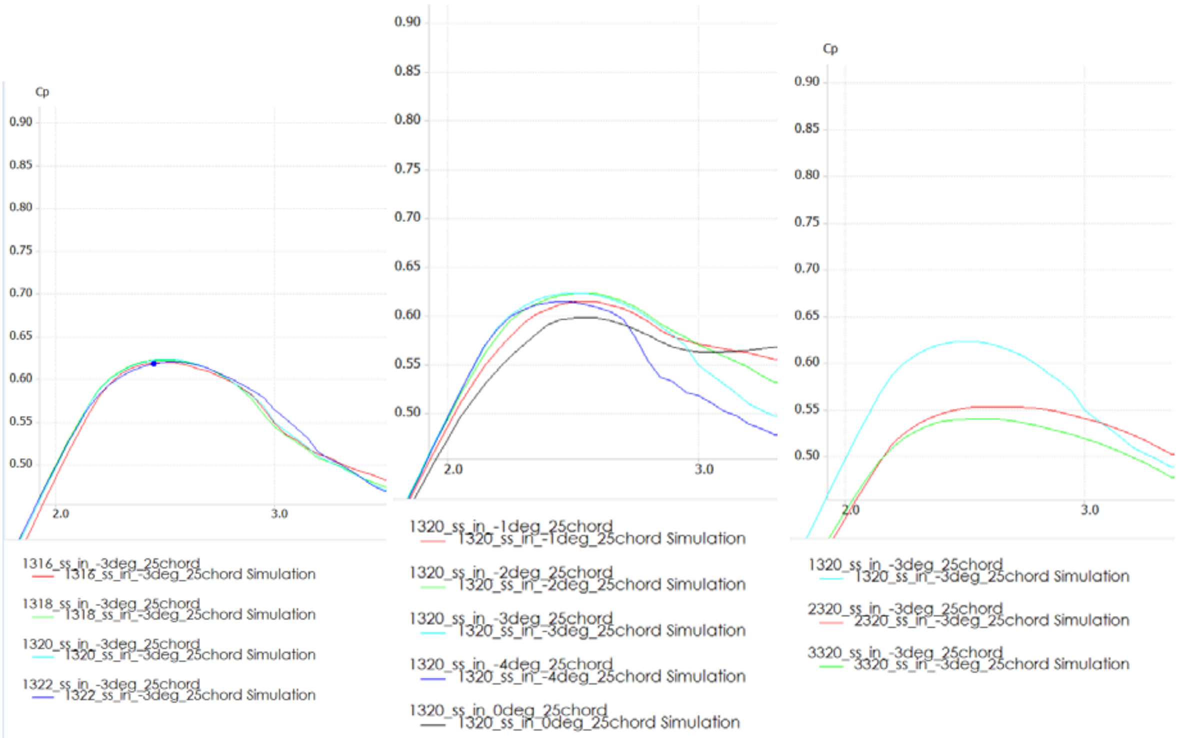

Figure 6: Effect of reduced chord on optimum thickness and pitch selection

TidGen 2.0 QBlade Streamtube Results Summary

Table 1 below summarizes QBlade streamtube analysis results for the two profiles and the baseline 1.0 foil.

Table 1. QBlade Streamtube modeling results.

Turbine Variant	*Analysis Model*	*Coefficient of Performance*	*Optimum Tip Speed Ratio*	*Power at 2.25m/s*
63-415, suction side out (TidGen 1.0)	Streamtube	0.44	1.9	39,000
1320, -3°, suction side in	Streamtube	0.63	2.25	50,500
1520, -3°, suction side in	Streamtube	0.63	2.25	50,500

QBlade Vortex Lifting Line Analysis

QBlade also offers a vortex method for analysis of turbines. This is much more computationally intense than the momentum streamtube methods, and not necessarily any more accurate. For a cross-flow turbine QBlade functionality is limited to calculation of CP.

Results are presented for a 1520 and a 1320 turbine (Figure 7). Results from the lifting line analysis differ from those of the streamtube analysis.

The streamtube results indicated that the 1520 and 1320 turbines would perform essentially the same.

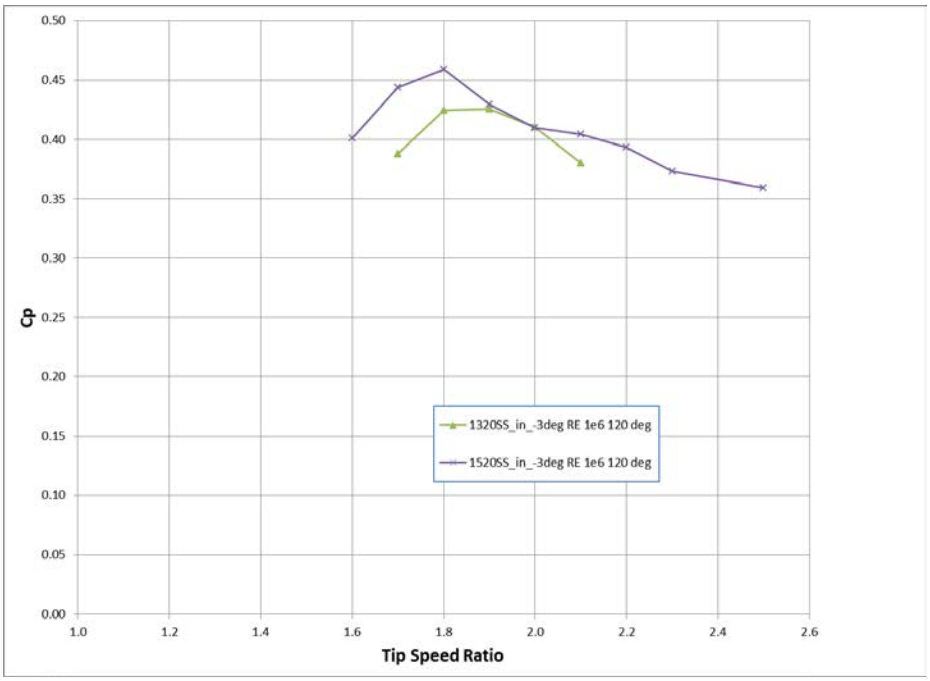

Figure 7: 1320 turbine as compared to 1520 turbine in Lifting Line analysis.

Additional lifting line analysis indicates that the -3° tilt on the 1520 foil is not the optimum turbine from a lifting line analysis (Figure 8). A +4° tilt appears to be significantly better than a -3° pitch, with relatively insensitive performance between +3 and +5°.

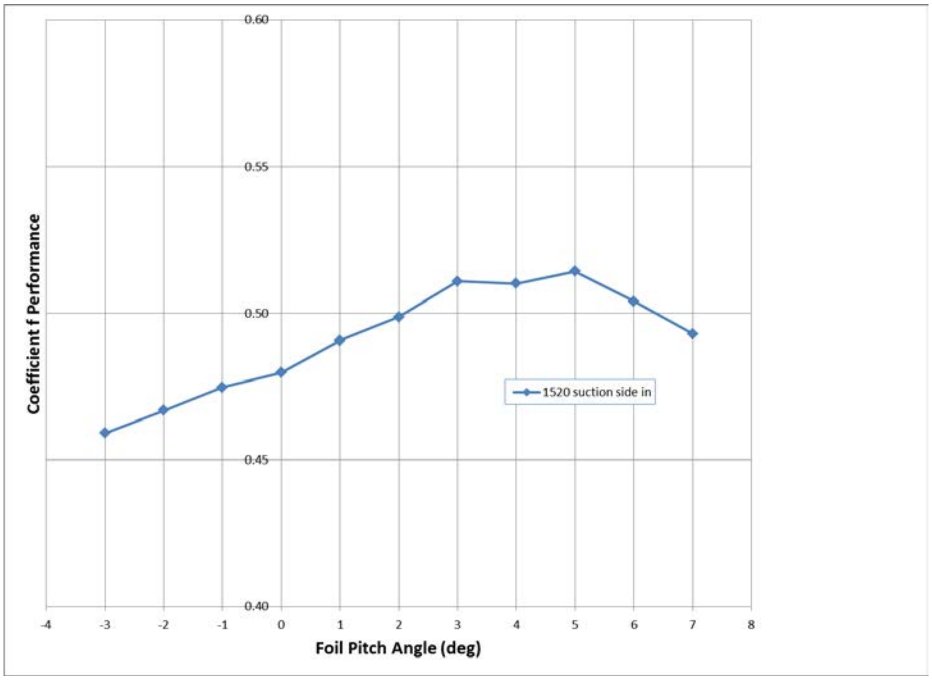

Figure 8: Effect of pitch angle on performance of 1520 turbine in Lifting Line analysis for a tip speed ratio of 1.8

Turbine Twist Angle

In the Lifting Line analysis the amount of turbine twist has a substantial effect on performance. With increasing turbine twist, the turbine efficiency increases, and the optimum tip speed ratio shifts slightly to larger values (Figure 9). At values above 135° the performance appears identical.

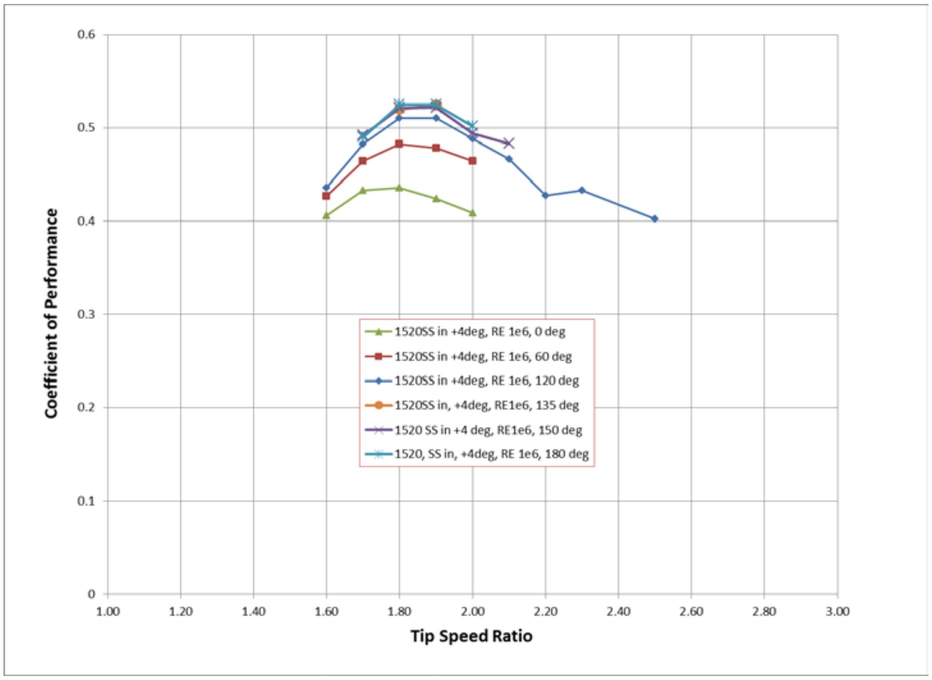

Figure 9: Effect of turbine twist on 1520 turbine performance

The near-turbine wake structure for a zero degree twist and a 120 degree twist is shown in Figure 10. The structure is more coherent for a zero degree twist and more diffuse for a 120 degree twist. The diffuse nature of the wake may possibly reduce the induction factors for the inflow, making inflow speed higher, as compared to the more structured wake for the 0 degree case.

There may be a different optimum pitch angle for different levels of turbine twist. However the efficiency appears higher for the large twist angles.

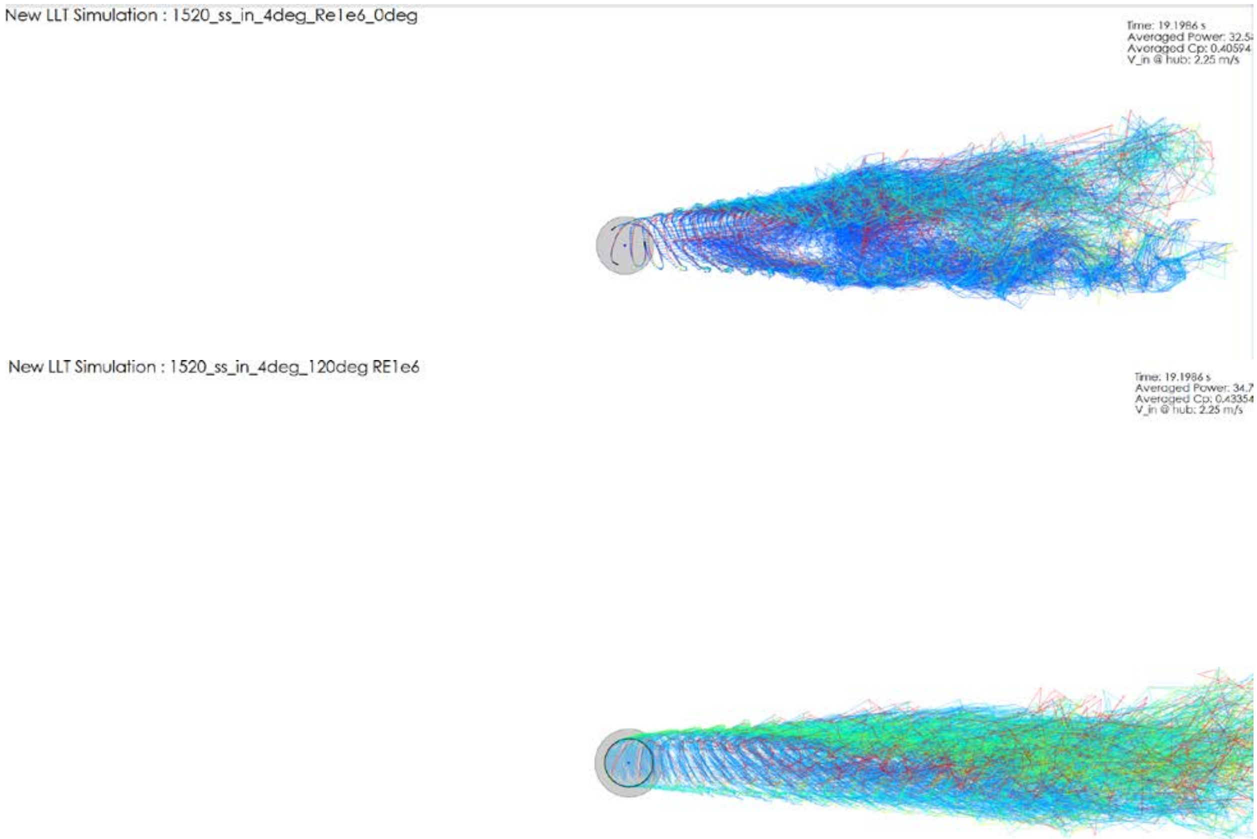

Figure 10: wake structure for 1520 turbine with 0 degree twist (top) and 120 degree twist (below). The color represents the strength of the vortex element.

QBlade TidGen 2.0 Lifting Line Analysis Summary

A summary of comparisons is shown in Figure 11 and Table 2 below.

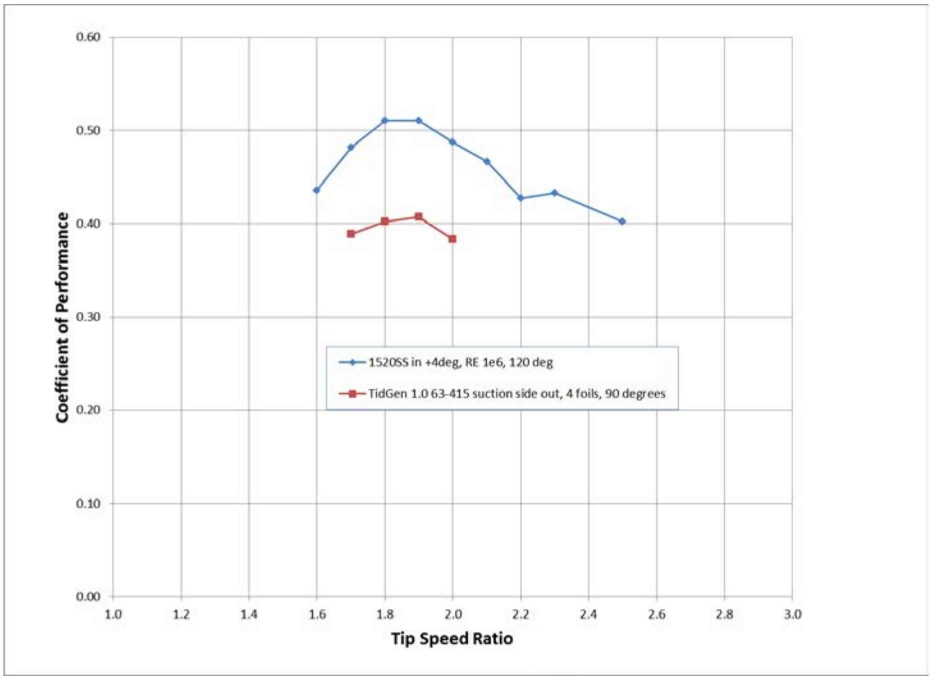

Figure 11: TidGen 2.0 compared with TidGen 1.0 Lifting Line Analysis

Table 2. Summary of analyses performed in QBlade.

Turbine Variant	*Analysis Model*	*Coefficient of Performance*	*Optimum Tip Speed Ratio*
63-415, suction side out (TidGen 1.0)	Streamtube	0.44	1.9
1320, -3°, suction side in	Streamtube	0.63	2.25
1520, -3°, suction side in	Streamtube	0.63	2.25
1320, -3°, suction side in, 120° twist	Vortex	0.43	1.8
1520, -3°, suction side in, 120° twist	Vortex	0.46	1.8
TidGen 1.0	Vortex	0.41	1.8
1520, +4°, suction side in, 0° twist	Vortex	0.44	1.8
1520, +4°, suction side in, 60° twist	Vortex	0.48	1.8
1520, +4°, suction side in, 120° twist	Vortex	0.51	1.9

3 Computational Fluid Dynamics

After the initial turbine design was complete the turbine was modeled with SolidWorks after which an additional CFD analysis was carried out with OpenFOAM. The model that was analyzed included a fairing as seen in Figure 12. The addition of this fairing is believed to improve the performance of the turbine by directing more flow into the turbine. The CFD analysis is a 2D analysis and does not account for twisting of the foils.

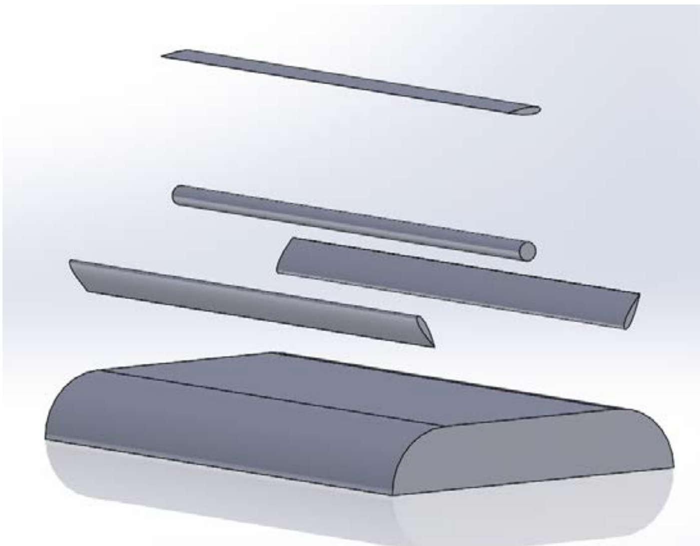

Figure 12: Advanced TidGen® turbine modeled in solidworks with a faring

The results from the 2D CFD analysis can be seen in Figure 13. The results show a maximum Cp of 0.57 at a TSR of 2.

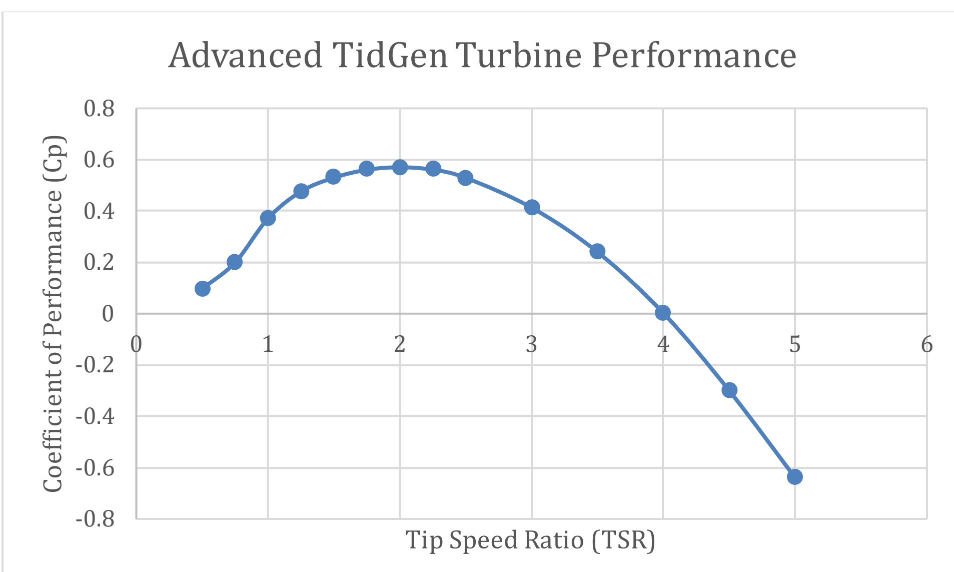

Figure 13: Advanced TidGen® 2D CFD results

As a means to establish a baseline for this CFD analysis, work done on the baseline TidGen® 1.0 was retrieved for comparison. There was a 2D CFD study carried out on the TidGen® 1.0 turbine in 2011 for ORPC under the TidGen® 1.0 project. These results can be seen in Figure 14 below.

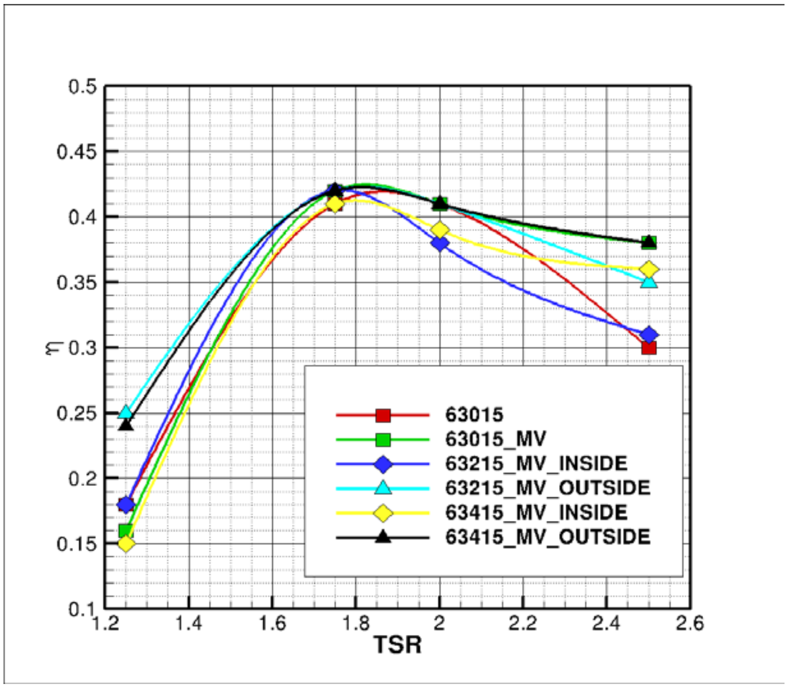

Figure 14: Baseline TidGen® 1.0 turbine performance

The maximum Cp for the baseline TidGen® 1.0 turbine which is the "63415_MV_OUTSIDE" is 0.425 at a TSR of 1.8.

By comparing the maximum Cp from the baseline and the Advanced TidGen® preliminary hydrodynamic design, it is possible to see the percentage increase in performance. With a target increase in performance of 35% we found that the actual increase in performance is 34.1% according to the 2D CFD analysis.

4 Performance Improvements

The turbine design effort for the Advance TidGen® is still underway. With each analysis, we have seen an increase in performance. Making comparisons to show progress over the baseline is necessary but complicated by the differences in analysis techniuqes.

In summary we have performed streamtube analysese, vortex lifting line analysese, and 2D CFD analysis. For the streamtube and lifting line analysis no fairing was included as these analyses are not capable of including external structure. For the 2D CFD the fairing was included. In all analysis the efficiency of the turbine has been increased over the baseline. However the TidGen 2.0 turbine has a different frontal area than the TidGen 1.0 turbine so power produced by each turbine does not scale as the efficiency.

Turbine Variant	*Analysis Model*	*Fairing*	*Coefficient of Performance*	*Tip Speed Ratio*	*Area per Turbine (m^2)*	*Number of Turbines*	*System Power at 2.25m/s (kW)*
TidGen 1.0	Streamtube	No	0.44	1.9	15.12	4	155.3
TidGen 2.0	Streamtube	No	0.63	2.25	13.75	8	404.6
TidGen 1.0	Vortex	No	0.41	1.8	15.12	4	143.8
TidGen 2.0	Vortex	No	0.51	1.9	13.75	8	327.9
TidGen 1.0	2D CFD	No	0.43	1.8	15.12	4	150.1
TidGen 2.0	2D CFD	Yes	0.57	2.0	13.75	8	366.0

5 Future Work

The fairing used in the preliminary turbine design CFD simulations was crude and not optimized. It is understandable that if the water is deflected into the turbine at the correct angle the turbine will be able to extract more power. As previously mentioned, if the solidity ratio is lowered the performance is increased. With this in mind it is understandable that by varying the chord length in the span wise direction, the performance will increase as the solidity decreases. Finally, optimizing the trailing edge may result in a slight increase in performance, but will certainly result in a reduction in wake effects.