COMPUTATIONAL SIMULATION OF TIDAL ENERGY GENERATION ESTUARY-SCALE SCENARIOS

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ABSTRACT

This project uses Computational-Fluid-Dynamics (CFD) to study Marine-Hydro-Kinetic (MHK) turbine arrays at a geo-physical scale, where turbulent wakes of MHK turbines can interact with estuary-scale flow dynamics. Secondary flows generated by bathymetric features can impact the survivability and efficiency of MHK turbines; and likewise, MHK turbine arrays can alter the aquatic environment. Mesoscale CFD simulations are performed via solutions of the Reynolds-Averaged Navier-Stokes (RANS) equations to capture the combined flow features generated by the coupling of bathymetry-induced flow and tidal turbine wakes. The objectives are: (1) to nest CFD simulations of the MHK turbine array environment (using the STAR-CCM+ code) within the estuary-scale flow (simulated by Regional-Ocean-Modeling-System, ROMS) for scenarios of hydrokinetic turbine power plant, and (2) to compare pre-installation and post-installation conditions. This study aims to inform the design of efficient, robust, and environmentally friendly large-scale arrays of tidal turbines.

1. INTRODUCTION

The key technical contribution presented here is the nesting of "micro-scale" CFD simulations into "estuary-scale" simulations from a typical regional ocean model. This report aims to address the following questions:

- What is the interaction of a tidal power plant with large-scale estuary flow dynamics? Are the possible changes measureable, and under what conditions?
- Is it possible to balance energy capture with favorable control of estuary flow dynamics? Can the enhanced turbulent kinetic energy in the wake of the turbines be taken advantage of to improve mixing and air entrainment (or other water quality measures)?
- What are the right computational methods, in terms of computational efficiency and fidelity, to study such contrasting spatiotemporal scales? Are available turbulence closure models adequate to provide predictions tractable to laboratory-scale experiments?

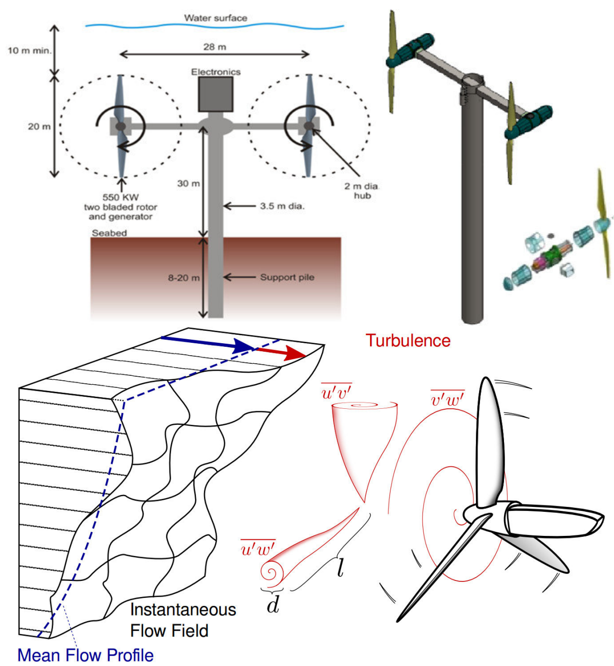

FIGURE 1. REFERENCE MODELS FOR HYDROKINETIC TURBINES [1,2,3,4]. THE ENERGY, SIZE, AND ORIENTATION OF EDDIES AND REYNOLDS STRESSES HAVE AN IMPORTANT RELATION TO TURBINE SURVIVABILITY.

2. METHODS

The computational simulation of the coupled turbine array/estuary flow is performed via three commonly-used software packages for CFD, oceanographic flow, and data processing:

- STAR-CCM+, for the simulation of MHK turbine array environment in a nested domain
- ROMS, for the simulation of the bathymetry/tidal-dominated flow in the estuary-scale domain
- Matlab, for the data exchange, and mapping of the ROMS data to create adequate boundary conditions for the STAR-CCM+ domain nested inside the ROMS-simulated field

2.1 Nested and Turbine CFD (STAR-CCM+)

The following sections describe the turbine model, adaptive-mesh-refinement, physics and turbulence closure models, and boundary condition implementations.

The turbine model is implemented in STAR-CCM+ via the Virtual Disk Models (VDM). The VDM models the effect of rotating bodies on the surrounding flow field via a momentum-conservation method. The geometry of the rotating element is not resolved; instead, the forces created by the rotor on the fluid crossing it are modeled as body forces distributed over the rotor-swept cylindrical volume. Similar models have been used on wind and MHK turbines and can resolve the near- and far-wake of MHK turbines [5,6]. The VDM method accounts for distribution of forces across the MHK turbine rotor in a manner extensively used in wind turbine design and research. The source term accounts for both the axial and the tangential velocity inductions as derived by the "Ideal Horizontal Axis Wind Turbine (HAWT) theory" with wake rotation.

To better represent atmospheric/oceanic type boundary layer flows, an ambient source term is added to the transport equations to counteract turbulence decay, disallowing the turbulence intensity to decay below the ambient condition. This ambient source term in the kinetic energy equation forces the flow, where needed, to maintain the specified level of ambient turbulence intensity. In the nested domain, adaptive-mesh-refinement (AMR) is developed to obtain more accurate solution in regions of strong turbulence or spatial gradients. The mesh resolution is adapted based upon the metric "turbulence intensity ratio", defined as the ratio of local value of turbulence intensity divided by the turbulence intensity averaged on the inlet faces. This metric easily identifies the turbine wakes as strong sources of turbulence, as well some of the strongest bathymetric features. This metric for the AMR has a strong influence only within the "core" volume mesh and does not affect the seabed mesh resolution. The meshing of the seabed is most critical, as there are strict requirements for the different turbulence closure models to maintain wall *Y+* values within a range of validity. Overall, the AMR proved effective in identifying and refining over key turbulent structures.

In the nested domain, several turbulence models are available to compare, in order of increasing fidelity: "SST k-Omega", "Two-Layer Realizable k-Epsilon", and "Reynolds Stress Transport". With these turbulence models, the approximation of the boundary layer is handled via the "all *Y+*" wall model in STAR-CCM+. In this case, the meshes are designed to maintain a range of *Y+* within ~30 to 300 to capture the turbulent boundary layer (below the buffer layer) along the seabed using the wall function approach.

The ROMS is able to track variation in the sea-surface elevation, under a hydrostatic and Boussinesq approximation. The STAR-CCM+ nested domain simplifies the sea-surface further via the "rigid lid" approximation where the sea-surface is a fixed and flat surface with "shear free" or "slip" boundary conditions. When the tidal elevation changes, as can be predicted accurately with ROMS, the STAR-CCM+ domain can be re-meshed and boundary conditions re-mapped at the new appropriate sea-surface elevation. When the sea elevation changes, the re-meshing and re-mapping process is relatively painless and made possible through Matlab and the Java API interface to STAR-CCM+. The STAR-CCM+ boundary conditions include velocity at the inlets, constant pressure at the outlets, and shear-free lateral bounds of the nested domain (sea surface and coastlines). Seabed surfaces are imposed by rough wall shear stress condition. In order to make the model more realistic and avoid artifacts from the boundaries, a vertical plane is placed at an approximate distance of ~10-15 meters away from the shoreline, resulting in the decoupling of the relatively shallow shoreline area from the domain. At the velocity inlet BCs, the ROMS velocity field is interpolated to initialize the three velocity components, and the TKE and dissipation rates are needed to initialize the turbulence closure. In the case of the Reynolds Stress Transport model, ROMS does not provided all values needed to initialize a solution, such as profiles of the Reynolds stresses and turbulence length scales; therefore, in this case previous field measurements can provide the initialization. Reynolds-stresses and length scales are derived from the compliantly moored Acoustic-Doppler-Velocimeters (ADV) previously deployed near Admiralty Inlet [8].

2.2 Estuary Scale CFD (ROMS)

One-way coupling is considered, where STAR-CCM+ is initialized by the ROMS along the perimeter of the nested domain. The turbulence closure model in ROMS parameterizes Reynolds stresses as turbulent fluxes via vertical eddy viscosity and diffusivity. In the Boussinesq approximation, density variations are neglected in the momentum equations except in their contribution to the buoyancy force in the vertical momentum equation. Under the hydrostatic approximation, it is further assumed that the vertical pressure gradient balances the buoyancy force. The equation of state for water density also allows tracking of temperature, salinity, and nutrients [9].

The bathymetry surface profile for the estuary-scale and nested simulations is extracted from the "PSDEM2005" digital elevation model, and "ainlet_2006_3" ROMS archived logs (datasets curated by the UW Oceanography

Department [7]). The gridded bathymetry within the nested Admiralty Inlet simulation was further smoothed to minimize hydrostatic inconsistency associated with the use of the sigma coordinate system with steep bathymetric gradients. The ROMS parent domain has been run at 183 meter resolution, with about 16 days of half-hourly saves. Boundary conditions from this came from a parent Salish Sea forecast [7]. The highest spatial resolution available is of 9-meter resolution within Admiralty Inlet, illustrated in Figure 6. The STAR-CCM+ mesh is based on this same bathymetry, but is further smoothed and resolved to smaller than 1 meter.

2.3 Data Exchange

A Matlab workflow, in combination with the Java API of STAR-CCM+, is developed to handle the automation of mapping the boundary conditions between ROMS and STAR-CCM+, and wrapping of optimization algorithms to automate setup, control and layout of the MHK turbines.

3. SAMPLE RESULTS

There are two scenarios to present now: an "idealized version" of a tidal strait, and then using actual bathymetry from Admiralty Inlet. The results shown here are using the SST k-Omega turbulence model of STAR-CCM+. A case where ROMS was used to directly force the boundary condition is not yet prepared. Alternatively, the inflow boundary conditions can also be specified similarly to logarithmic wind profiles of classical atmospheric boundary layer flows.

3.1 Tidal Strait

The flow within Admiralty Inlet is characteristic of a tidal straight with a dominant sill and headland. An idealized model of a narrow tidal channel with a sill, representative of the conditions in Admiralty Inlet can reproduce similar flow features (such as counter-clockwise rotating eddy South-West of Admiralty Headland). This idealized shape of tidal channel provides a testbed for studying different layouts of tidal power plants. In this case, ROMS is not used to force the flow. Alternatively, the inlet conditions can be generated by a pre-cursor simulation in which the outlet is re-mapped into the inflow boundary. First removing the sill from the channel, and then allowing the flow to recycle from the outlet-to-inlet will become a fully developed open channel flow. The "Tidal Strait" with a sill is shown in Figure 2, without any turbines present and using the inlet conditions from "recycling method" pre-cursor. This mesh is custom made in Matlab to have smooth Gaussian shaped sills and coastlines, it also has an option to add synthesized seabed roughness using fractal geometry. The resolution is ~5 meters on seabed, and ~0.5 meters localized around the turbine wakes due to the adaptive mesh refinement.

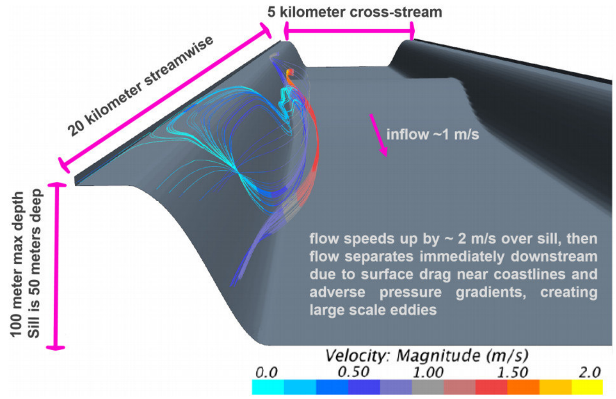

FIGURE 2. VIEW LOOKING UPSTREAM OF THE "TIDAL STRAIT" CASE WITHOUT TURBINES. STREAMLINES HIGHLIGHT THE RECIRCULATING EDDY AND UPWELLING DOWNSTREAM OF THE SILL AND ALONG THE COASTLINE.

A hypothetical power plant with 49 turbines (total 53.9 MegaWatt capacity) is tested in two layouts: a uniform staggered grid and a "tidal fence" (see Figure 3). In the "tidal fence" case, "row 1" and "row 2" of turbines produce the smallest contribution to the total energy but also redirect flow into the central part of power plant and increase power output from rows 3, 4, and 5. In the "uniform staggered grid" case, the energy extraction, as well as the thrust forces on each dual-rotor turbine, are more uniform. Figure 4 shows the individual power contribution from each turbine rotor. Considering that both power plant layouts generate approximately the same amount of power (~28 MegaWatts mechanical rotor power), this suggests that perhaps neither layout is highly optimized in terms of turbine placement. But there are other notable differences, such as the structure and size of the recirculating eddy downstream of the sill. Comparing between the layouts, and shown in Figure 3a-b, there is a noticeable difference in the length of coastline in contact with this type of upwelling flow (just downstream of the turbines).

3.2 Admiralty Inlet

A hypothetical 11 MegaWatt tidal power plant composed of 10 DOE RM1 turbines is deployed in Admiralty Inlet. To study the effect of complex bathymetry, the turbines are deployed in a site with shallower water compared to previously proposed turbine deployments at this site [8]. Figure 5 shows the depth averaged velocity of a 30-minute snapshot during a strong flood tide; notice the large scale flow features generated by headlands, sills and basins. The estuary-scale models provide resource characterization and comparison of ambient flow features to the effect of hydrokinetic turbine power plants.

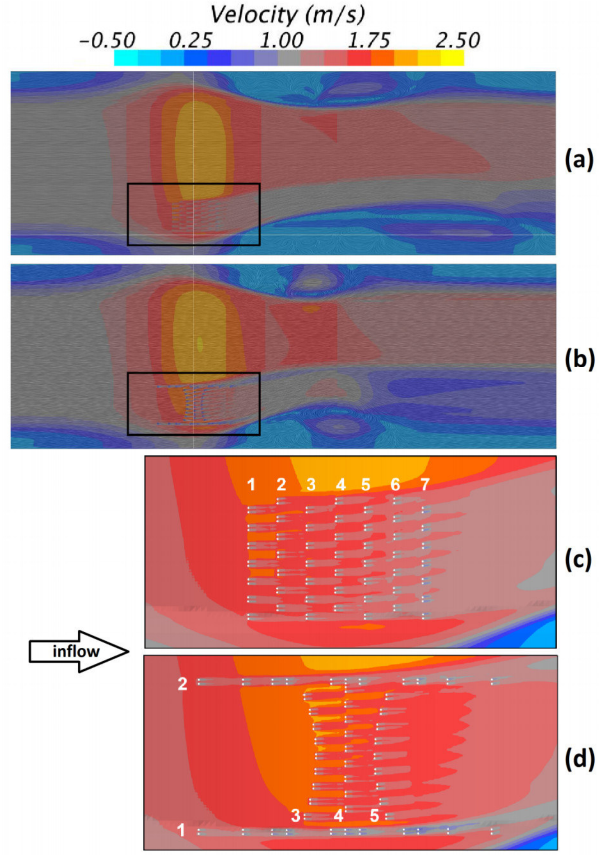

FIGURE 3. THE TIDAL CHANNEL IS TESTED WITH TWO LAYOUTS OF TURBINES: (A) IS THE UNIFORM STAGGERED GRID AND (B) IS THE "TIDAL FENCE", WITH A ZOOMED VIEW OF THE LAYOUTS IN (C) AND (D).

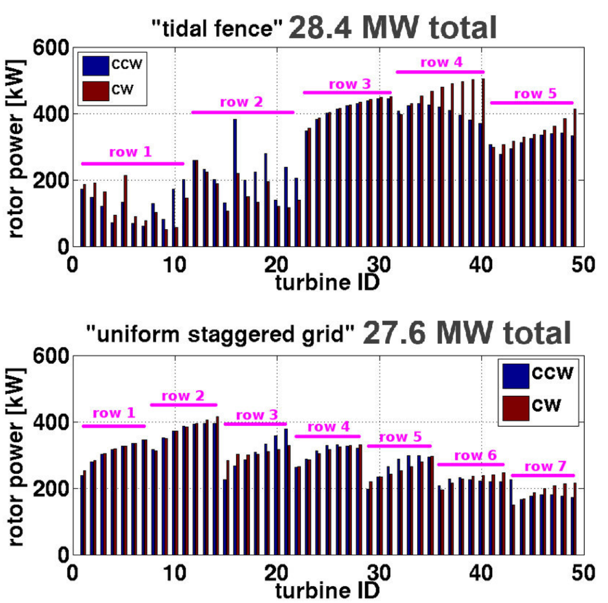

FIGURE 4. THE TOTAL POWER PRODUCED BY THE "TIDAL FENCE" (TOP) AND "STAGGERED GRID" (BOTTOM). ROTORS ARE INDICATED BY COUNTER-CLOCKWISE (CCW) AND CLOCKWISE (CW)

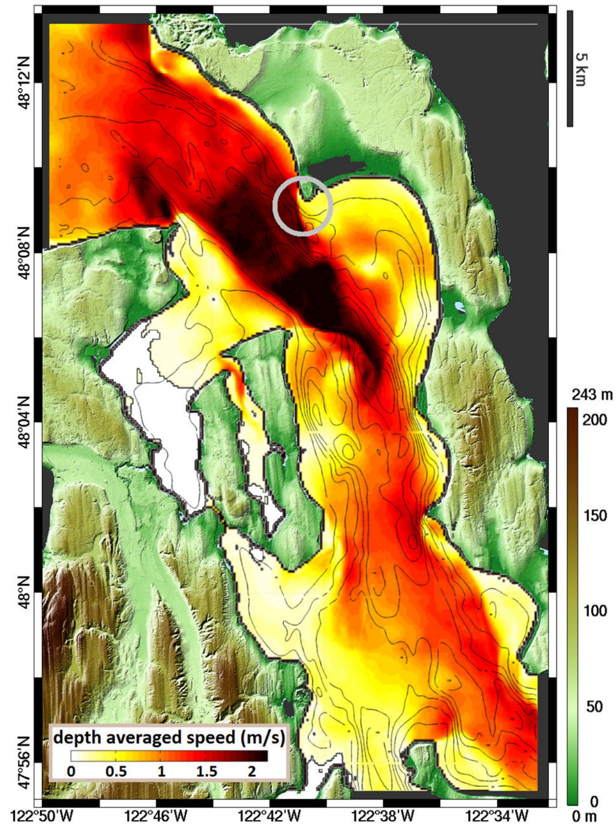

FIGURE 5. THIS IS THE PSDEM-2005 TOPOGRAPHY OVERLAID ON THE AINLET_2006_3 ROMS SIMULATION. SHOWING DEPTH AVERAGED VELOCITY DURING A STRONG FLOOD TIDE, WITH ISOBATH CONTOUR LINES OVERLAID. A CHARACTERISTIC FEATURE IN ADMIRALTY INLET IS LARGE RECIRCULATING EDDIES THAT SEPARATE OFF THE COASTLINES OF THE HEADLAND. THE CIRCLED AREA AROUND ADMIRALTY HEADLAND SHOWS THE EXTENT OF FIGURES 6 AND 7.

The STAR-CCM+ mesh is acquired from the PSDEM_2005 gridded dataset at 9 meter resolution, and then can be further refined and smoothed as an unstructured trimmer mesh. The ROMS structured mesh in the Admiralty Inlet region was run at 183 meter resolution, so the mapping of ROMS to STAR-CCM+ would be interpolating data from a 183meter grid to possible ~1 meter grid resolution. Some further type of "data smoothing" is likely to ensue once the ROMS to STAR-CCM+ coupling is more completely developed.

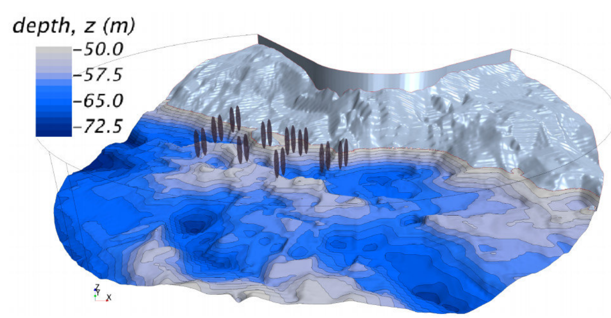

FIGURE 6. THE NESTED DOMAIN, SHOWING SMOOTHED BATHYMETRY AND LOCATION OF THE TURBINES RELATIVE TO HEADLAND AND SILL.

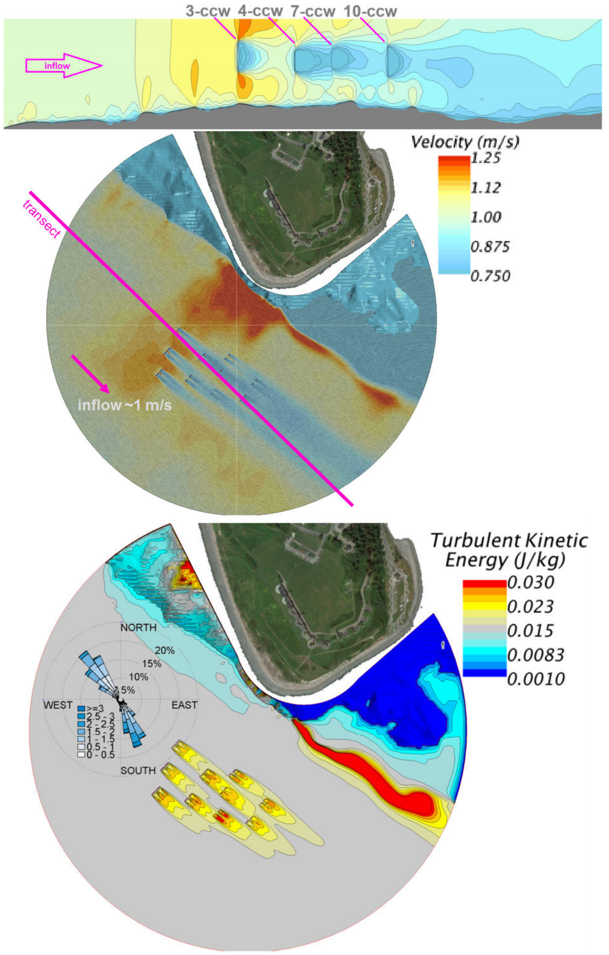

FIGURE 7. SATELLITE IMAGERY OF ADMIRALTY INLET OVERLAID ON NESTED CFD SIMULATION. [TOP]: SLICE-PLANE OF VELOCITY ALONG A STREAMWISE TRANSECT, INTERSECTING FOUR OF THE ROTORS, (DEPTH IS EXAGGERATED BY 10 FOR VISUALIZATION). [MID]: SLICE-PLANE OF VELOCITY, AT DEPTH INTERSECTING THE TURBINE CENTERLINES, AND [BOTTOM] SHOWING THE TKE.

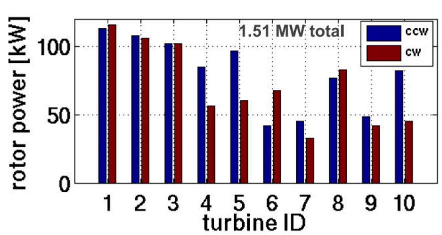

FIGURE 8. POWER OUTPUT FROM THE 10 TURBINE LAYOUT IN ADMIRALTY INLET.

Figure 7 (top) clearly shows the speedup caused by bathymetric features and interaction of wakes upon the seabed and sea surface. Figure 7 (mid/bottom) highlights the velocity field and turbulent kinetic energy upon a visualization plane at approximately the depth of the turbine centerlines and intersecting the seabed along coastlines. Compared to levels of TKE already produced from the bathymetry, the TKE produced by tidal turbines is of similar spatial extent but lower intensity (measurable but comparatively small). This type of simulation is helpful in learning how the proximity to headlands, sills and basins could affect turbine performance.

4. CONCLUSIONS & FUTURE PROSPECTS

The nested domain within ROMS can reproduce characteristic bathymetry-dominated flow features, and complete simulation runtimes within acceptable timeframes. The groundwork has been laid to automate the nesting of STAR-CCM+ domains within a provided ROMS dataset. Some ongoing work includes: running 1-way nested simulations at many key directions within the “wind rose” (Figure 7), and using the 2-week long ROMS boundary conditions at 30-minute snapshots to drive the nested domain. An optimization problem could also be posed, in which the design variables include tip-speed-ratio control, and yaw control of the individual turbines; this would inform how to optimize power production or alter the estuary currents in a particular fashion. After exploring the turbulence closure and verifying grid independence, it would be interesting to enable the adjoint flow solver available within STAR-CCM+. The adjoint method could be useful in finding optimal placement and control of turbines, and to identify where the highest sensitivities and uncertainties exist in the flow field. Source codes developed in this report are available at [10].

ACKNOWLEDGEMENTS

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