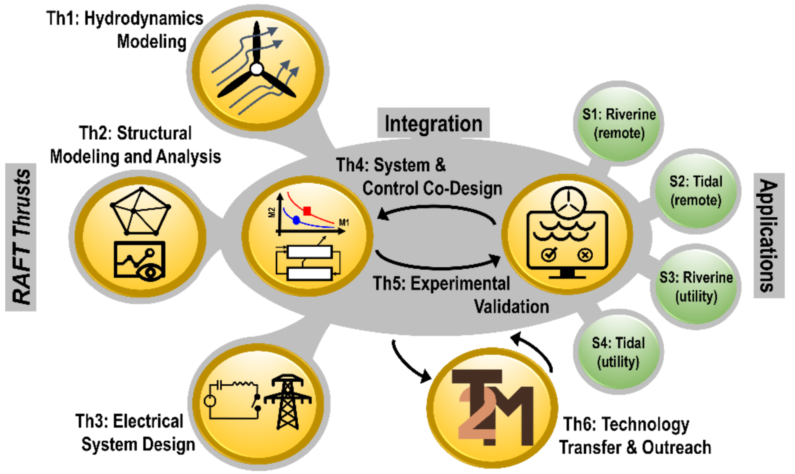
2021 ARPA-E Energy Innovation Summit™

ARPA-E CHANGING WHAT'S POSSIBLE

RAFT
Reconfigurable Array of High-Efficiency Ducted Turbines



RAFT: Reconfigurable Array of High-Efficiency Ducted Turbines for Hydrokinetic Energy Harvesting

University of Michigan-Ann Arbor, Rutgers, Oregon State University

Technical Overview: RAFT team

RAFT – Reconfigurable Array of High-Efficiency Ducted Turbines

PI: **Jing Sun**,
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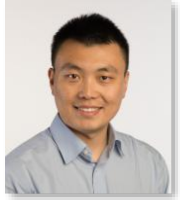
Th3: Electrical System Design

Ted Brekken
Yue Cao

Oregon State University

Th1: Hydrodynamics Modeling

Kevin Maki
Yulin Pan



Roger Wang

RUTGERS

Th4: System & Control Co-Design

Joaquim Martins
Reza Amini

Onur Bilgen

RUTGERS

Th2: Structural Modeling and Analysis

Onur Bilgen

RUTGERS

Th5: Integration & Validation

Th6: Technology Transfer

*Th: Research Thrust

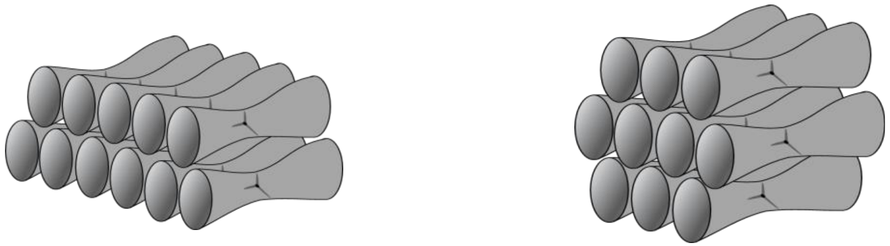
Technical Overview

RAFT
Reconfigurable Array of
High-Efficiency Ducted Turbines

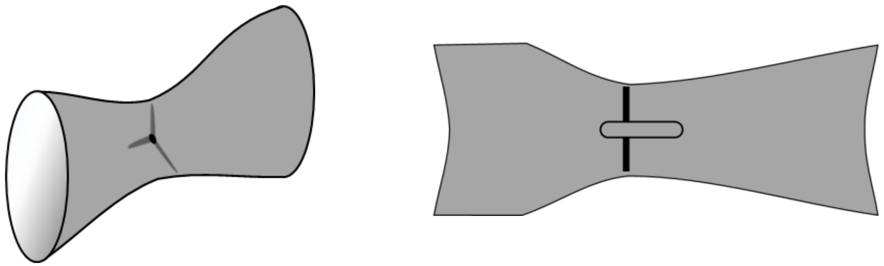
- Develop and demonstrate a novel Hydrokinetic Turbines (HKT) concept with:
  - **Modularized** architecture with **reconfigurable arrays**;
  - **Ducted design** for flow conditioning;
  - **Folding blades** for dislodging debris;
  - **Multi-scale and multi-discipline** optimization and **control co-design (CCD)** at micro and macro levels.

- The main **objectives** of the project:
  - **Demonstrate** RAFT concepts;
  - Leverage **CCD** to dramatically reduce **LCOE**;
  - Develop **multi-physics models**;
  - Develop design processes and **optimization tools.**

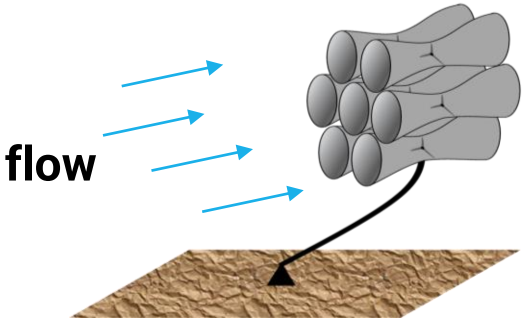
One Integrated Solution Applicable for Tidal, Riverine, Utility, and Remote Applications



Reconfigurable Array



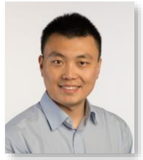
Ducted Design



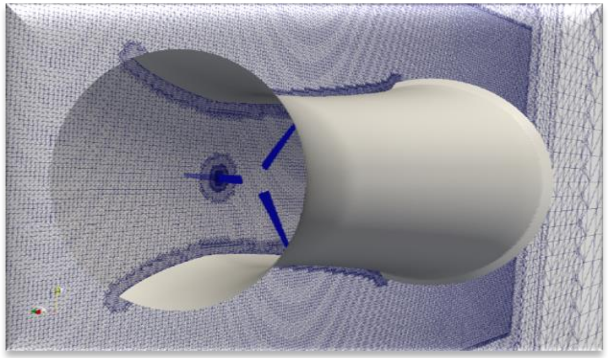
Moored Submerged Array

Thrust 1: Hydrodynamic

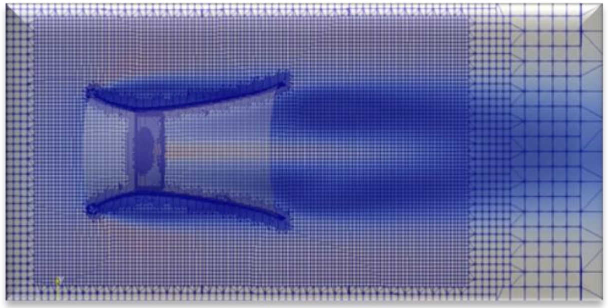




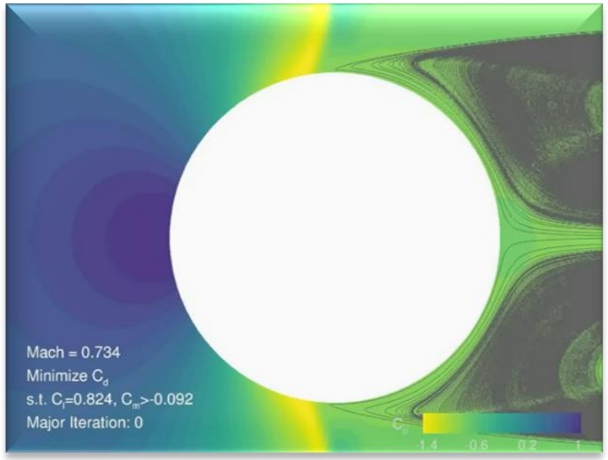
- **Single micro turbine modeling and design optimization:**
  - **OpenFoam:** CFD modeling for turbine performance with duct;
  - **DAFoam:** Geometry optimization via adjoint method.



- **Macro array modeling and optimization:**
  - **Bi-fidelity CFD** model (full geometry vs. body force) for array performance;
  - **Array optimization** via surrogated-based method.



- **Macro array modeling and optimization:**
  - **FLORIS** to account for wake interactions;
  - Aim for both **riverine and tidal environments**;
  - **Farm-level** optimization via **DRESSA**.



Thrust 2: Structural

- **Conceptual design and parametric geometry:**
  - **A tool that generates** the “wet” or so-called **outer-mold-line (OML) geometry of all designs**;
  - **Visualization and qualitative study of** different turbine geometries and array assemblies;
  - Rough **estimation of the basic size and mass** properties.

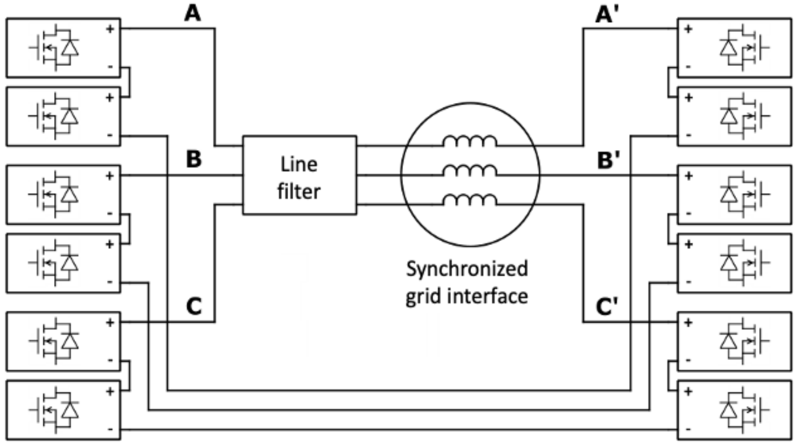
- **High-fidelity structural modeling:**
  - **FE model** for rigid-mounted turbines and turbine arrays;
  - **Internal topology design** to achieve minimum mass-, transportation-, hydrodynamic-, and generator-induced deformations, and the associated stresses.

- **Low-fidelity structural modeling:**
  - **Physics-based models** for rigid-mounted and moored-submerged turbines, and turbine arrays;
  - **Two-way coupled** fluid-structure and generator-structure interactions predictions;
  - System design to minimize mass-, transportation-, hydrodynamic-, and generator-induced deformations, and stresses.

Thrust 3: Electrical


- **Achieving high efficiency, high reliability, low cost:**
  - **Modularized power electronic converters** with silicon carbide (SiC) devices and integrated cooling;
    - Less-rated more-efficient cheaper devices,
    - Distributed losses and improved water cooling,
    - Scalable voltages up to medium voltage, less ohmic loss,
    - Smoother power and reduced passive elements,
  - **Fault-tolerance** and **health monitoring**;
    - Fault bypass allowing module offline maintenance,
    - Reinforcement learning for condition changes: biofouling,
  - **Generator control** and control for **microgrid connection**;
    - Max generator power, min power fluctuation, min stress,
    - Grid-following and grid-forming grid support,
  - Environmental friendliness and adaptation;
    - Minimal electric or magnetic noise emission,
  - Overall electro-mechanical-thermal design optimization.

A proof-of-principle multi-level cascaded H-bridge inverter



Motor drive utilizing a multi-stack multi-level SiC based DC-AC inverter, with fault tolerance

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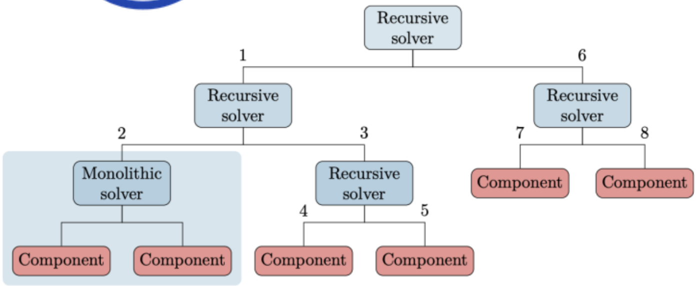
Thrust 4: System & Control Co-Design

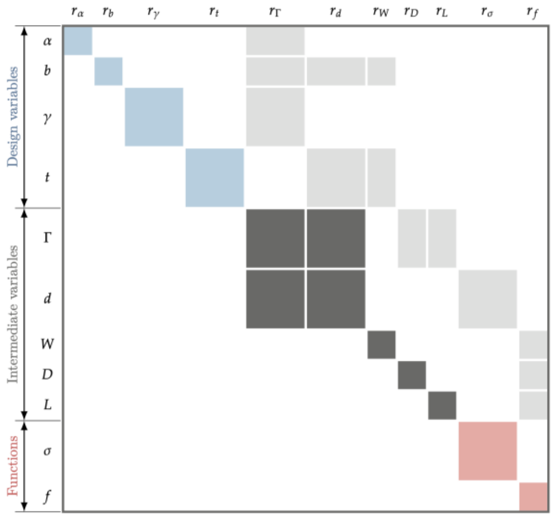


- **Multi-physics modeling and analysis:**
  - **Strongly–coupled** low-order **lumped-parameter** multi-physics modeling;
  - Analysis of **theoretical bounds** for system responses;
  - Theoretical and experimental **system identification** and validation.



- **Hydrokinetic turbine design optimization:**
  - Leverage **OpenMDAO**;
  - Modular **architecture optimization**;
  - Efficient solution of **coupled hierarchical models**;
  - Efficient computation of coupled derivatives via **coupled adjoint method**.

- **Control Co-Design and Real-time Control:**
  - **Dymos** open-source framework built with OpenMDAO;
  - Efficiently **computes gradients** via an adjoint approach;
  - **Control co-design integration** with hydro-electro-structural design optimization;
  - **Real-time, distributed, and constrained load and power generation optimization** via model predictive control (MPC).



Thrust 5: Validation and Demonstration

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- **Integrated system testing at MHL:**
  - Physical model basin, 109 m (L), 6.7 m (W), and up to 3.4 m depth;
  - Powered, manned carriage, and an unmanned sub-carriage;
  - Plunging wave-maker for regular and irregular wave generation;
  - Model scale experimental **testing and demonstration** of the integrated **RAFT** system (single and multiple units).

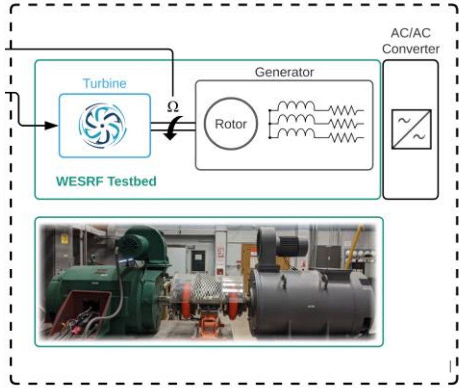
Aaron Friedman Marine Hydrodynamics Lab. (**MHL**)

- **Benchtop, wind tunnel, and hydro-environmental testing at Rutgers:**
  - **Closed-circuit** low-speed tunnel with a 71 cm × 51 cm test section;
  - **Fully automated** Eiffel type tunnel with max flow speed of 72 m/s;
  - **Motion capture** and high-sensitivity **load cells** for automated benchtop experiments;
  - **Hydraulic, wave, and sediment flume**, volumetric hydraulic benches.

Closed-circuit Low-Speed Wind Tunnel

RUTGERS

- **Electrical system testing at WESRF**
  - 750 kVA **dedicated utility power**;
  - **Multiple rotary test beds** up to 300 hp;
  - Multi-physics **energy storage banks**;
  - Medium-voltage **high-power power supplies**.



Wallace Energy Systems and Renewables Facility (**WESRF**)

Oregon State University

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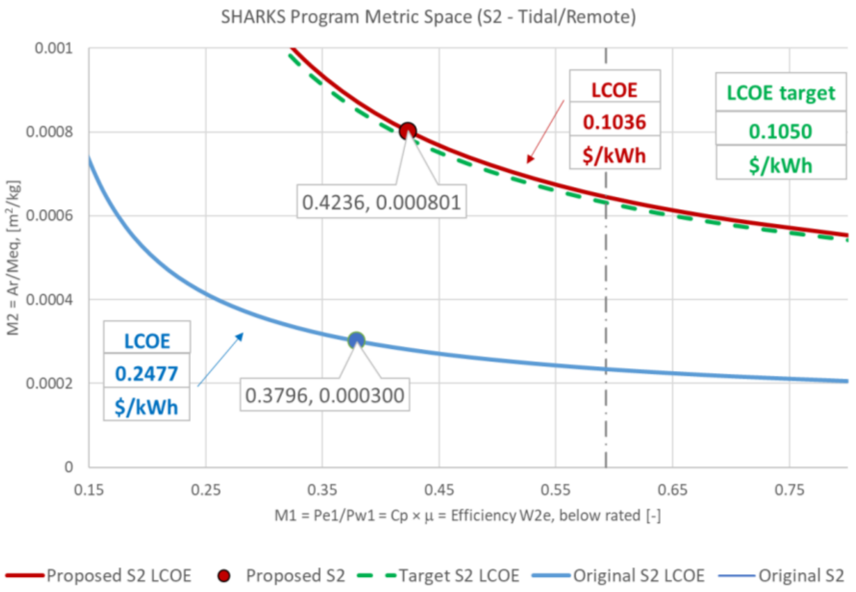
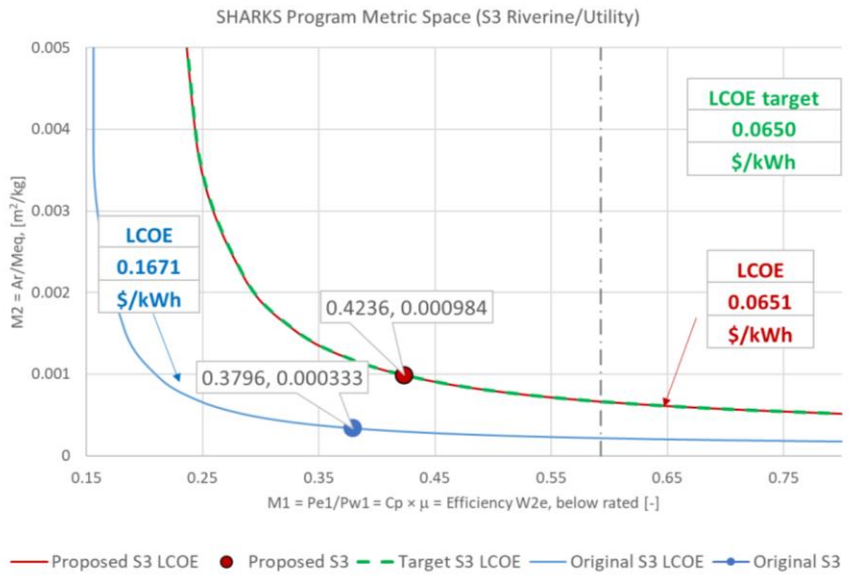
Path to Target LCOE

Key RAFT Contributions	LCOE, M1, and M2 Variables Affected
Reconfigurability and Modularity	Water turbine availability, Structure manufacturing, OpEx/kW
Control co-design and Power regulator	Max. power coefficient, Resilience and robustness
Elimination/reduction of floating/mooring system, as well as tower/cross-arm/columns	Mass reduction
Less number of drive train components	Drive-train losses, Mass reduction, OpEx/kW, Turbine availability





- **Key T0 (environmental) activities:**
  - **Filtering** of debris and marine species, **dislodging** of entangled species, and **bio-fouling cleaning** through duct inlet screen, and **folding blades**;
  - **Alleviating noise** and vibration through electrical module design and system control;
  - **Assessing marine animal collision** risks, and physical impact on environmental flow conditions, sediment transport.

Project Impact

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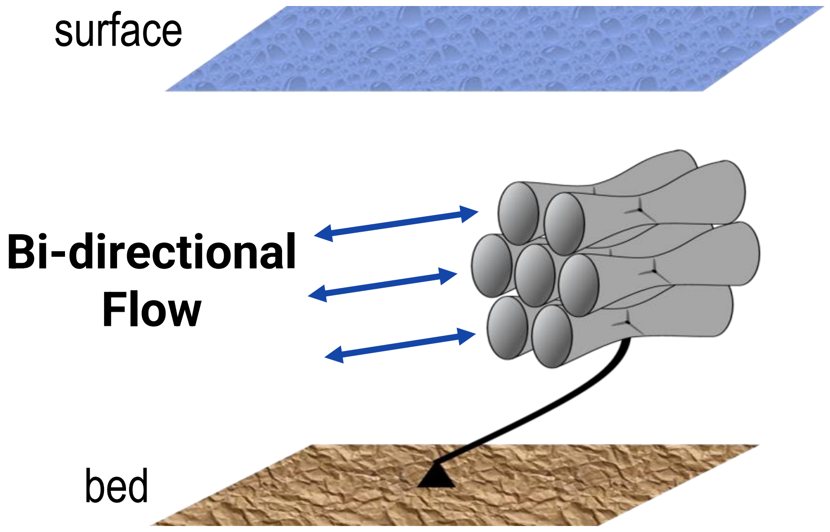
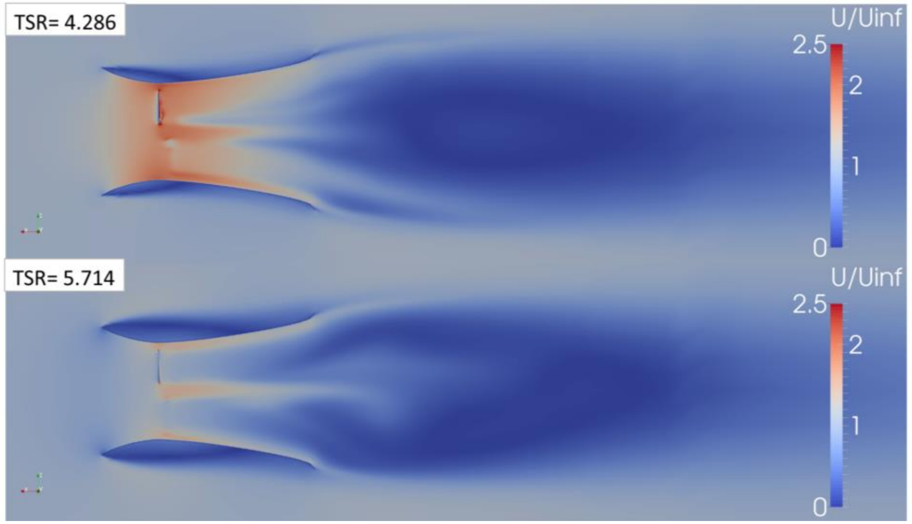
- **Innovations and Transformational Impacts**
  - **Modularized** architecture with **reconfigurable** units:
    - Significant reduction in LCOE, CapEx, and OpEx;
  - **Scalable** design **adaptable** to river-bed/sea-floor topographies;
  - **Control co-design** enabling **resilient** operation in the harsh marine environment:
    - Multi-disciplinary optimization to exploit synergies between physical and control design spaces;
  - **Distributed load control** for optimal power production:
    - Innovative differential control for active yaw and pitch control of the array assembly,
    - Leveraging the environmental condition and coordination among RAFT units.





*TSR: tip speed ratio

Tech to Market Plan

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- **Design Cases:**
  - One integrated solution applicable for S1, S2, S3, and S4 (tidal, riverine, remote, utility);
    - Focus on S2 and S3 (tidal/remote, riverine/utility),
  - Adoption of moored-submerged type of RAFT for ocean current.
- **Target Stakeholders/Market:**
  - Renewable and offshore energy industry;
  - Suppliers and the US government.
- **T2M Barriers**:
  - No pre-existing commercialization partner(s);
  - Manufacturing and supply chain for HKT.

Reconfigurable Micro-Turbine
as building blocks

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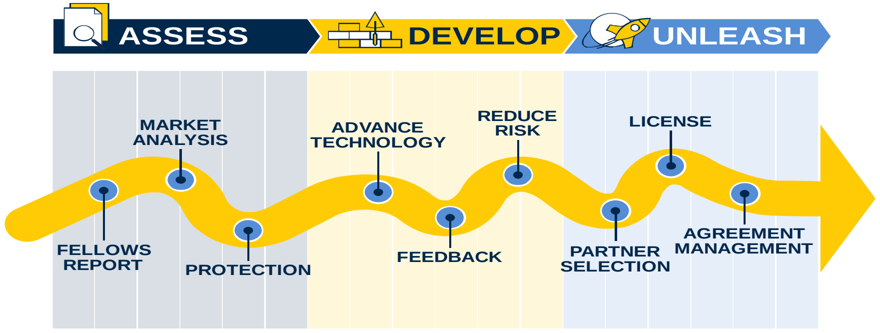
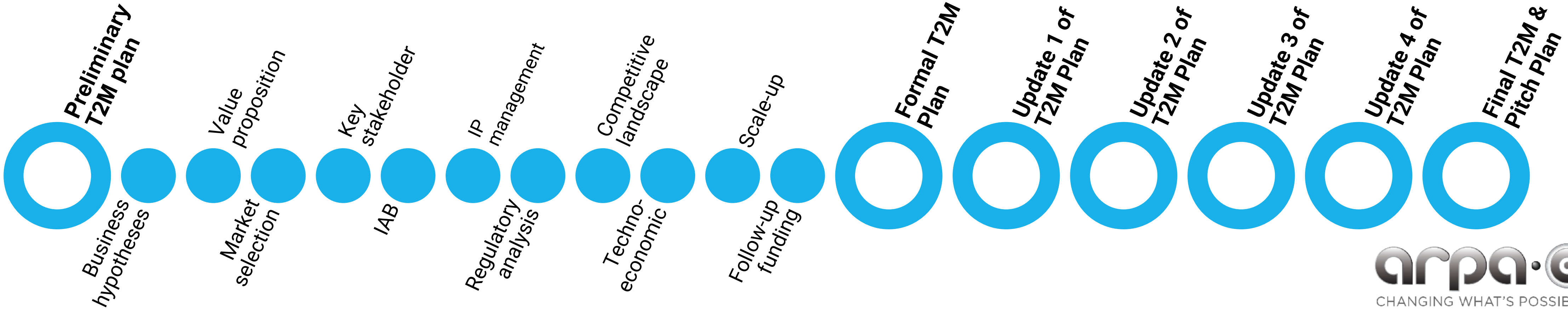
Removal of key barriers for T2M
(fabrication, manufacturing, CapEx, OpEx, …)





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http://umich.edu/~racelab/arpa_e_sharks.html

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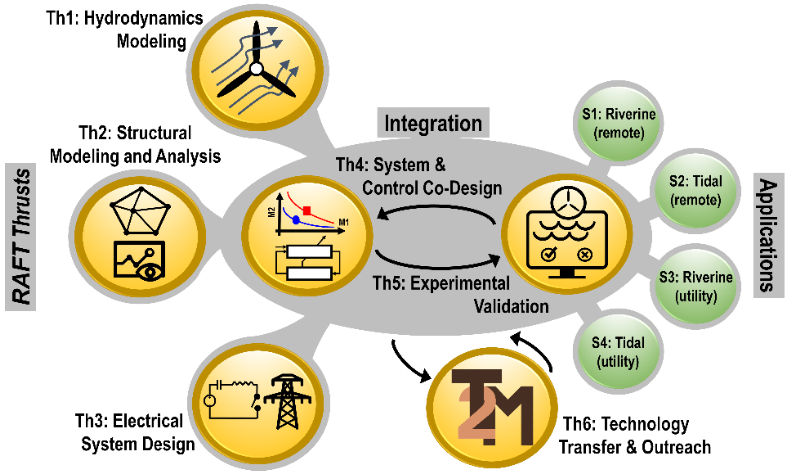

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