Climate-Aware Wide Area Coordination of Distributed River Energy Resources

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Water, solar and wind energies are essential for sustainability. Distributed solar and wind farms proliferate, but water energy harvest is trapped in a century-old damming paradigm with high up-front costs, ecological impacts, and ongoing costs as obstacles for barge traffic (alleviated by locks that must be manned and maintained). And yet, as a river runs down to the ocean, there is an enormous amount of kinetic energy that could be sustainably harvested, if it can be done without impoundments. Environmentally friendly alternatives, or hydrokinetic power projects, attempt to extract this kinetic energy in the river at a relatively small, local scale. Our vision is a coherent cyber framework for (1) effectively planning and operating ecologically and economically sustainable run-of-the-river hydropower systems in the developing world, (2) supplementing existing conventional hydropower in the developed world, and (3) for restoring dammed rivers to natural flows while still supplying power.

Electric power systems are in the midst of a paradigm shift away from centralized control towards greater levels of distributed market-driven, decision-making, with increased reliance on supply resources that are not directly controllable by system operators. Although well understood by the technical community, across the breadth of society a very simple proposition and its implications are not often recognized: *electrical power cannot be stored in any substantial quantity at reasonable cost; we must exactly match generation to demand as it happens*. The 20th century centralization of power supply made this practical – particularly by using hydroelectric dams as surge supplies that are easily switched on and off. System operators are experimenting with mechanisms to incorporate distributed and variable resources, but the extent of the system needs for procurement and pricing are not yet well-understood [1–5]. As long as distributed resources are not a major player in synchronous electrical grids, such problems are manageable. However, the existing infrastructure and control systems for central power generation are simply inadequate for efficient large-scale distributed power generation. Thus, continuation of the 20th century paradigm limits our future options for sustainable energy and locks us into large, centralized power stations.

Presently, industry is struggling with adapting the 20th century infrastructure to meet these 21st century energy challenges. A key reason is that we lack proven scientific and engineering foundations for handling uncertainties and interactions given the complexities of forecast weather, climate, power demand, and distributed power generation. Developing the next generation infrastructure requires we re-think the very basis of monitoring, communication, and control systems (*i.e.*, the "*cyber*" component) on one hand, as well as our ability to forecast weather, climate, and societal demand (*i.e.*, the "*physical*" component) on the other hand. This is why taking a truly cyber-physical approach to address the sustainability problem can make a difference in the long run.

To this end, the distributed control problem in the context of river networks becomes of central importance. These networks are a compelling example of a complex cyber-physical system where societal needs meet nature, and where we are just beginning to consider the computational aspects of distributed power generation. Rivers are environmental integrators of the uncertain and evolving processes of rainfall, groundwater exchange, and landscape runoff that are strongly affected by a changing climate. As societal servitors, rivers are a nexus of hydropower, transportation, water supply, waste transport, agriculture, flood management, and economically valuable natural habitats for recreation and commercial exploitation. Furthermore, the variety of uses and demands on water supplies are often overlapping and sometimes in direct competition: *e.g.*, a full reservoir maximizes available water during a drought, but decreases flood control capacity and poses greater downstream risks. The use of rivers for conventional hydropower through damming is now recognized to have significant long-term ecological impacts – what might be called "emergent disasters." As such, development of new hydroelectric capacity has slowed down in the industrialized world, but such concerns are often ignored in the developing world. Fortunately, there is a technological solution on the horizon with hydrokinetic Run-Of-the-River (ROR) hydropower and low-head hydroplants – a distributed generation approach akin to wind turbines. Even in countries that have made substantial investments in conventional hydroelectric assets, distributed ROR hydrokinetic units have substantial technical potential [6].

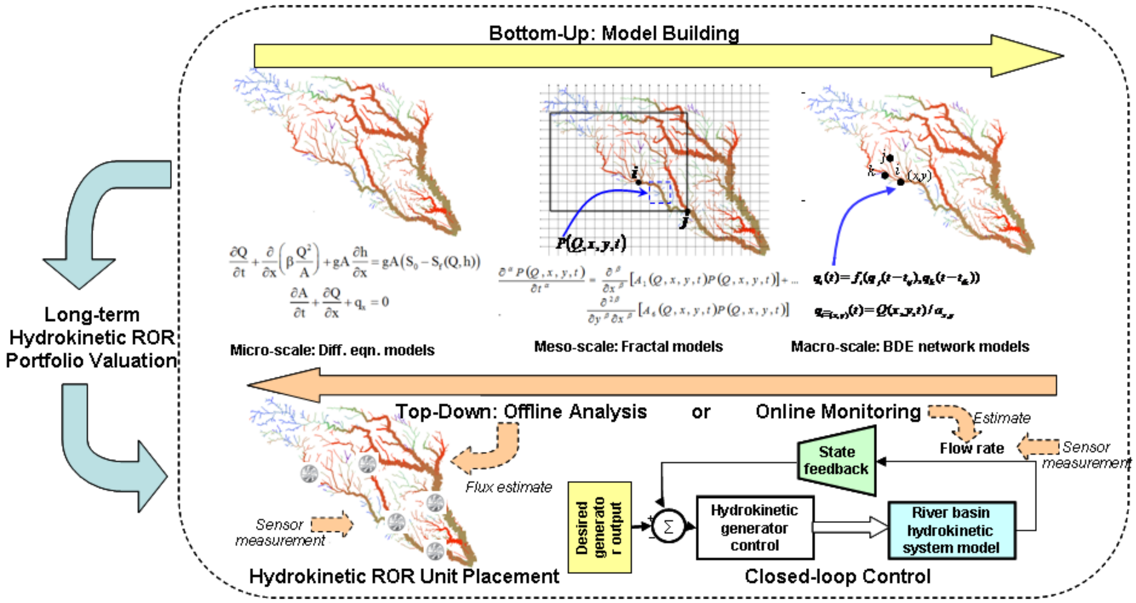

Figure 1: Overview of modeling, analysis, control methodology and policy/economic implications.

To address the shortcomings of ROR hydropower given its uncertainty in matching generation with consumer demand there is a clear need for computational tools for modeling and simulation involving both cyber and physical components of large river networks with small footprint hydropower. Therefore, a methodology for *multi-scale* river network modeling and analysis that allows accurate, yet efficient, capturing of the important parameters for estimating energy production becomes essential. For comprehensive coverage, such a methodology should include:

- ***Computational models*** for river network flows based on abstractions that can be handled efficiently, yet provide accurate predictions. We believe that at macro-scale, models can be based on Boolean delay equations (BDEs) which have been used in the past for abstract modeling of colliding/cascading failures in complex systems [7][8] - examples include El Nino modeling, earthquake prediction [9], or biological networks [10][11][12]. Meso-scale modeling require fractal characterization of river flows. Fractal behavior is widely spread in natural and technological systems and has been exploited to improve performance modeling or control mechanisms for silicon systems [13] or cyberphysical systems [14]. Finally, micro-scale models are based on efficient solvers for the differential equations governing the water flow dynamics for river networks [15][16][17].
- ***Multi-scale simulation tools*** based on the above models that provide fast estimation of energy production and an early gauge of any generation-demand imbalance. Coarse-grain, full river network models can be used for fast, qualitative identification of critical scenarios for further analysis by meso-scale models. Subsequently, critical subnetworks can be analyzed more accurately by micro-scale models. This multi-scale framework can be used in offline mode (for determining a priori the location of ROR projects) or online (for monitoring the output of existing ROR projects). The framework's foundation is a ***mathematical formalism that*** allows for multi-scale modeling of river flow behavior, precise placement of ROR power plants to match energy demands, and feedback-based control to determine the active/sleep modes for ROR that match various seasonal or transient energy demand profiles.
- A comprehensive ***computing infrastructure*** relying on highly-parallel computing and application-specific platforms that demonstrates the efficacy of the proposed modeling and simulation methodology. To this end, we conjecture that Field Programmable Gate Array (FPGA) based full system emulation and GPGPU-based acceleration of the simulation framework using real datasets that are publicly available or gathered using off-the-shelf sensors deployed in river basins of interest are likely to provide fast, yet sufficiently accurate estimates.
- Models for the ***long-run valuation*** of ***portfolios of small-scale ROR*** hydrokinetic power generation units under flow uncertainty, and an informed ***policy assessment*** of replacing conventional hydroelectric assets with distributed hydrokinetic units. The economic modeling needs to leverage the simulation tools and multi-scale modeling to assess the predictive value of utilizing ROR hydrokinetic units for providing different services to an electricity market (*e.g.*, scheduled energy, meeting peak energy demands; fast-response reserve energy), while the policy

modeling must consider benefits to ecosystem services (and potential net costs to electric grids, if any) associated with conventional hydroelectric dam replacement.

Figure 1 shows the components of the proposed paradigm that interact during the phases of model building, offline simulation, online monitoring, and runtime control. During the model building phase, micro-scale models based on differential equations are implemented and validated against real data. Rapid analysis for large river basins is enabled by building meso-scale models tested against the differential equation micro-scale models. The meso-scale uses fractal/self-similar models that characterize probability distribution functions for junction flow rates to extract the fractal characteristics of the river network. These are further used to build the macro-scale, abstract model relying on stochastic BDEs (SBDEs) which determines efficiently, but *qualitatively*, the critical portions of interconnected river networks and proactively predicts under- or over-production scenarios. Once built in a *bottom up* approach, the three models are integrated in a multi-scale analysis framework that is able to simulate in a *top down* manner large sets of interconnected river networks. First, the macro-scale SBDE model is used to determine where the flow per unit of area (or flux) is likely to be under or above critical thresholds, while the meso-scale and micro-scale models are in turn used to *zoom in* these regions and determine more exact, *quantitative* answers. These estimates, along with real measurements from sensor data will be used as inputs to the proposed control and optimization formalisms. New computational aids for optimal placement and dynamic control of dispersed ROR systems will work hand in hand with long-term portfolio valuation formalisms that enable assessment of distributed ROR projects at various time scales ranging from hours and days to years or decades.

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