Effects of real-time electricity pricing on welfare and investment, with inter-hour elasticity and high penetration of renewable energy

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Vision. As power systems adopt larger shares of intermittent renewable energy, it will become increasingly important to reschedule electricity demand to the times of day when wind or solar power are most abundant. Wind and solar power on any given day have a time profile that is significantly different from current loads. As these resources are scaled up to meet an increasing share of demand, they will begin to exceed current loads during some hours, while falling short in others. This means the marginal cost of production will approach zero during some times, while remaining high at other times. This can also pose a significant barrier to further adoption of renewable power, especially solar: once daytime loads are mostly satisfied by solar power, the usable contribution from another MW of solar capacity becomes small, while costs per MW remain the same, making further solar development unaffordable.

These problems in the intra-day balancing of loads and renewable power can be mitigated by use of large-scale electricity storage. However, in many regions it is impractical to develop pumped storage hydro power, and other storage technologies have high cycling costs; e.g., lithium-ion batteries have a high capital cost and a finite number of cycles before they must be replaced, giving rise to a cost of about $0.15 per kWh stored and released. Other battery technologies have similar variable costs. Consequently, we expect a persistent difference on the order of $0.15/kWh between high-renewable-production times each day and low-renewable times, unless enough demand can be shifted from low-renewable to high-renewable times to avoid using batteries.

This points to a key potential benefit of real-time pricing (RTP) of electricity at marginal cost – it can give customers an incentive to shift loads from times of day when renewable power is scarce or loads are high, to times when renewable power is abundant or loads are low. And this incentive can adapt from day to day as weather and load conditions change. With the advent of ubiquitous computing and communication technology, inter-hour substitution of electricity consumption may become available on a large-scale at a low cost, as electricity-consuming systems automatically retrieve real-time prices and forecasts and adapt their operations to minimize cost, without impinging on customer utility. For example, smart water heaters can choose the cheapest times to reheat each day, smart electric-vehicle chargers can choose the best times to charge within an extended plug-in period, and air conditioner controllers can pre-cool or make ice during cheap times and then “coast “during expensive times.

This project will conduct the first study of the effects of inter-hour demand elasticity on the optimal investment plan and customer welfare in a power system with a very large share of renewable power. We expect to show that inter-hour elasticity (in addition to same-hour elasticity) can significantly reduce the cost of reaching high renewable-energy targets, and can also significantly improve welfare. This project will also make available an open-source power system model that can be used by other researchers to study the

effects of arbitrary multi-hour demand functions on an operational or investment time scale, using an exceptional amount of supply-side detail.

Previous work. A number of previous studies have estimated the effects of electricity RTP on investment and operation of the power system and on social welfare. These studies have generally considered customers with simple, constant-elasticity demand functions (Borenstein 2005; Borenstein and Holland 2003). These studies are able to model customer choices about the tradeoff between amenity and cost during each hour, e.g., reducing air conditioning during hours with high electricity prices. Other studies have estimated elasticity of substitution for electricity consumption between different hours of the day, but have not modeled the effect of inter-hour elasticity on system design or operation (Faruqui and Sergici 2010; Hopper, Goldman, and Neenan 2006; Patrick and Wolak 2001).

However, we are not aware of any previous studies that have incorporated inter-hour elasticity into studies of the effects of RTP on power system design and operation and social welfare. Further, the studies that have estimated inter-hour elasticities have not considered automated forms of demand response that could primarily provide much higher inter-hour substitution elasticities.

Holland and Mansur (2008) consider the effect of within-day load shifting on pollution emissions, and argue that RTP will reduce the variance of load and thereby affect emissions. This study, however, takes the generation infrastructure as given, and cannot identify from historical data precisely how much loads will shift in response to price. They found minimal likely influence of RTP on emissions. However, looking prospectively at a future generation and renewable energy goals, electricity supply could become much more variable, and perhaps more complementary with renewable energy and thus with pollution reduction goals.

Project plan. This project will rely heavily on the open-source SWITCH power system planning and operations model, which has recently been extended with the ability to incorporate arbitrary demand functions into the unit-commitment process, as well as the ability to model spinning reserve requirements and costs, fuel market transitions and nodal marginal electricity pricing. These capabilities complement SWITCH's pre-existing ability to choose optimal multi-decade investment plans based on hourly loads and the hourly availability of wind and sun at hundreds of project sites (Fripp 2012; Nelson et al. 2012; SWITCH 2015; also see Appendix). For this work, we will use a version of SWITCH that has recently been calibrated for conditions on Oahu, Hawaii's most-populated island.

We will first develop simple demand functions for multiple classes of load, each of which has a constant elasticity of demand for same-hour electricity consumption. This demand system emulates those typically used in earlier research, without inter-hour substitution, and will serve as a baseline (e.g., Borenstein). We will then consider demand systems that, in addition to the overall price response, have a share of baseline load that is perfectly substitutable between hours of the day.

Finally, we will consider demand systems built from a sum of nested constant-elasticity-of-substitution (CES) utility functions. The outer nest of each demand accounts for substitution between electricity and all other goods, and parameters can be calibrated based on existing estimates of overall electricity demand response and the expenditure share of electricity. The inner nest accounts for the elasticity of substitution of electricity consumption across different hours of the day. Share parameters for each inner nest will be calibrated based on baseline loads, baseline fixed prices, and an assumed elasticity of substitution. The aggregate demand will be comprised of a weighted sum of demands with different elasticities of inter-hour substitution, each of which returns baseline loads at baseline fixed prices, but each of which is differentially responsive to changes in relative prices across hours. By varying weights across the more or less elastic demand components, we can illustrate a wide range of substitution possibilities.

We will then use the SWITCH power system planning model to choose optimal investment plans for Oahu for the next 30 years, using each of these demand systems with dynamic marginal-cost pricing of electricity. We will also use SWITCH to choose an optimal investment plan with average-cost pricing of electricity. In each case, the power system must meet Hawaii's renewable power targets ranging from 30% in 2020 to 100% in 2045. This exercise will allow us to trace out the relationship between overall cost of a high-renewable system and the time-substitutability of demand. We will also experiment with more and less aggressive targets to assess how the relative savings from inter-hour substitution vary with the renewable penetration level

A longer run goal is to quantify the amount of demand substitutability we can reasonably expect. We can estimate such possibilities using experiments, ex-post analysis of load shifts in response to historical time-of-use rates or demand charges (fees based on maximum annual load). Alternatively, we can take a forward-looking approach by unpacking the load curve into some of its largest constituent components and costing out specific technologies that could shift loads from one time to another. Such technologies could include smart water heaters that can pre-heat during low-price times, ice storage in air conditioning systems, flexible scheduling of water pumping and irrigation, water treatment, desalination, or auto-lighting adjustments.

Preliminary work. We have conducted limited tests already, using two simple demand models. In the first case (Figure 1), demand each hour is independent, with an elasticity of 1.5%. In the second case (Figure 2), 70% of demand has a same-hour elasticity of 1.5%, and 30% of the load is perfectly substitutable between hours (infinite elasticity). Neither case included battery storage (which has since been added to SWITCH), so these are highly schematic results. In the first case, the optimal power system design includes only enough renewable power to meet the 40% RPS by 2030. In the second case, the optimal design includes 54% renewable power by 2030, and welfare is improved by about $500 per household per year compared to the first case.

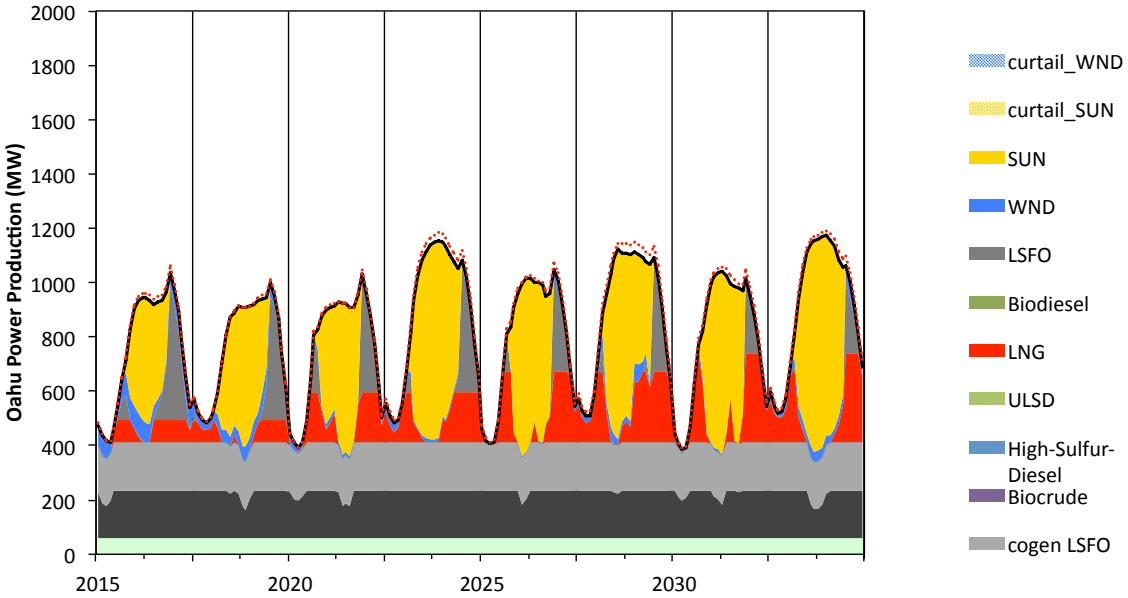


Figure 1. Baseline demand (red dotted line), reshaped load (black line), and supply from various fuels during 2 days in 2015, 2020, 2025 and 2030, for an optimally designed system with only same-hour elasticity (-1.5%)

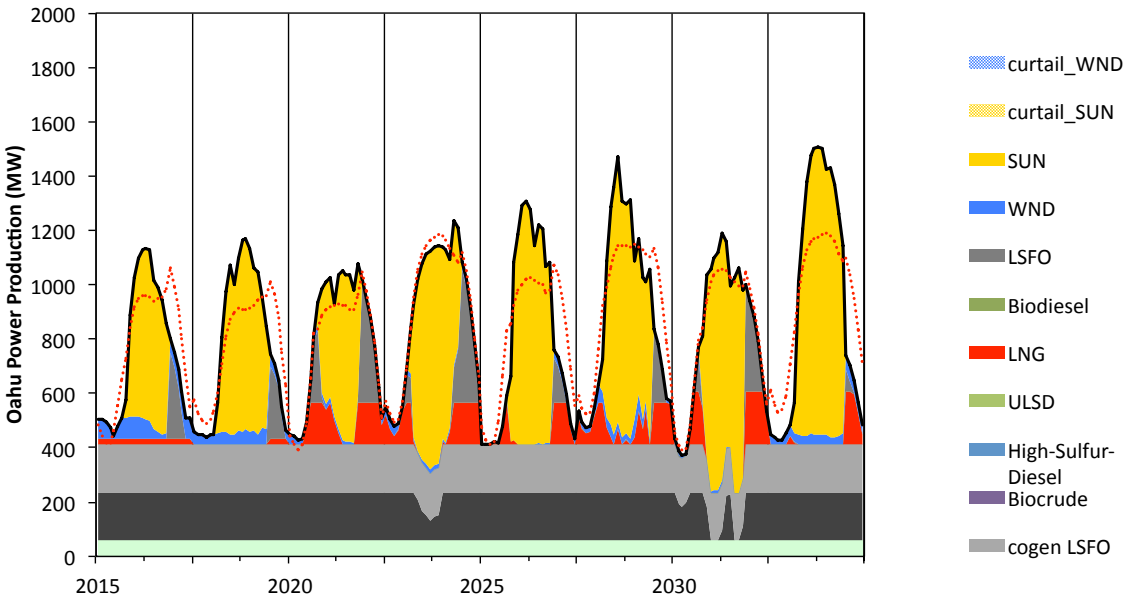


Figure 2. Baseline demand (red dotted line), reshaped load (black line), and supply during 2 days in 2015, 2020, 2025 and 2030, for an optimally designed system with 1.5% same-hour elasticity for 70% of load and infinite inter-hour elasticity for 30% of load.

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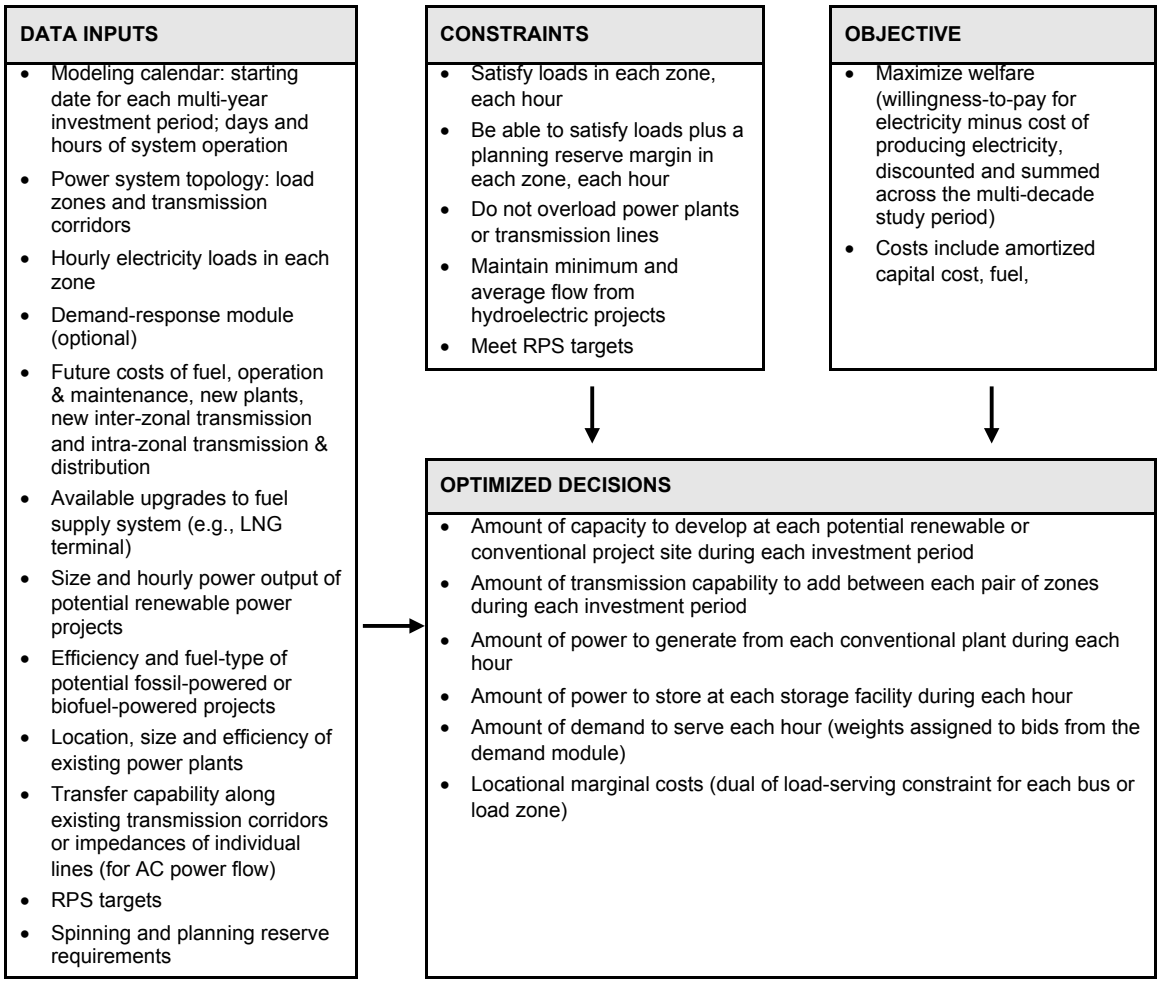
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Appendix – SWITCH Model

SWITCH is a mixed-integer linear programming model designed to optimize investment choices in electric power systems over multi-decade periods. The diagram below shows its main inputs, constraints and decisions.



SWITCH is a primal model of investment and operation of the power system (i.e., a production planning model). To maintain fast computation times, it includes only linear components in the main model. However, it has recently been extended to integrate arbitrary demand systems via Dantzig-Wolfe decomposition. This formulation is guaranteed to converge for any convex demand function.

Demand systems are added to SWITCH by writing a "demand module" in the Python or R programming language. This module must contain a function which accepts a vector of prices for each hour of one day, and reports back a "bid" showing the amount of power that would be consumed during each hour at those prices, as well as the maximum amount the customers would be willing to pay for that bundle of consumption (the

demand module can also consider baseline loads and prices, as well as the date and weather conditions on that day). The combined model is solved iteratively as follows:

1. Solve primal model with a baseline load level. Extract dual values of load-serving constraints as tentative hourly prices.
2. Report tentative prices for all hours on each day to the demand module. Demand module reports back hourly consumption and willingness-to-pay (WTP) for that bundle (one vector and one WTP value for each day).
3. Primal model is re-solved. While solving, the main model constructs a new vector of demand levels for each day by assigning weights to all the bids it has received from the demand module. The main model can choose weights that maximize welfare (WTP minus production cost), but the weights must sum to 1.0 each day (e.g., 50% of bid 1, 20% of bid 2, 30% of bid 3). The same weights are applied to the WTP for the individual bundles in order to estimate WTP for the combined bundle. (In the first iteration, there will only be one prior bid, which will receive a 100% weight.)
4. New tentative prices are calculated from the duals of the load-serving constraints. Then the process returns to step 2, and repeats until converged (usually about 25 rounds).