# Collusive Smart Homes

Proposed Investigation into Tacit Collusion in Peer-to-Peer Trading on Microgrids

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Abstract: Promises of a near future built on distributed energy resources (DERs) are everywhere. The benefits of such a future, combined with microgrids and automated control algorithms, includes increased resilience, avoided transmission losses, and more price-responsive demand. Achieving this future, however, depends upon networked systems of digital agents with access to vast data, and this point concerns many. Up to now, though, mainly the privacy risks have been treated. I propose to join the microgrid literature with a separate thread of research into AI game theory, specifically investigating the possibility of market power exercise via tacit collusion and potential policy remedies to it.

# Contents

# Introduction

The continuing digitization of daily life promises conveniences and efficiencies in many sectors of the economy, from online commerce to public transportation. In energy too, paradigm shifts are expected in the everyday generation and consumption of energy, contingent only upon the continued success of Moore's law. Along with the benefits they bring, though, new technologies can threaten what we appreciate about the past. Data privacy is dear to many critics of technology firms today, and is something they fear to lose. Another specter, gaining prominence, is the hyped ability of artificial intelligence to grow out of control and to govern itself or us.

In this paper I propose to join two active threads of research. The first, into electrical microgrids: reconfigurations of the power grid that privilege distributed energy resources and consumer preference. The second, into the antitrust consequences of smart homes that can self-regulate and inter-communicate. By executing a computer simulation of a microgrid composed of smart homes, I would search for evidence of emergent, collusive behavior in these agents. To be clear, I will not actually present the results of such a simulation here; the goal of this paper is to fill a gap in power systems research by educating about an issue that is prominent in another academic field. Consumer welfare in a distributed energy future should not be taken for granted.

The rest of the paper proceeds with a background section covering the three important aspects of the proposed simulation: Distributed Energy Systems that form the infrastructure of the power system, Smart Homes on this power system and the Control Algorithms that drive them, and finally issues of Market Power and Collusion that could yield anti-competitive pricing outcomes. The simulation itself is then described at some length, with discussion touching on execution frameworks, learning algorithms, and evaluation methods. Certain details surrounding its hypothetical implementation are necessarily left undeveloped. I conclude with a section describing regulatory and policy suggestions that would be useful when confronting the problem of colluding smart homes in reality.

# Background

## Distributed Energy Systems

Today's power systems are in the middle of great change as they face what Morstyn et al. call the "energy trilemma": serving zero-carbon energy affordably and reliably to all.[1] Visions for the details of the transformed grid vary widely, but most predict a continuation in form of the superimposed network system of today. (This is a bulk high-voltage system connecting large-scale generation and consumption over long-distance, layered on top of spider-webbing distribution networks that serve residential and small-to-medium-sized commercial and industrial loads.) Despite this continuity in the network, major changes are expected and underway in the generation and consumption of electricity.

Generation will trend cleaner and vary more in size and site; of specific interest for this paper is the growth of disaggregated distributed energy resources (DERs) arrayed in communities and connected to the distribution network either directly (as in the case of community solar) or indirectly (as in the case of behind-the-meter storage systems). Adoption of DERs is occurring around the USA even in localities where it is neither financially supported through tax subsidies, procurement programs, or utility programs, but it is especially visible in the jurisdictions with active support programs, such as the Brooklyn Microgrid project.[2]

Consumption of electricity will also change, broadly by upending the traditional assumption that power demand is price inelastic. This change is not limited to the proliferation of demand response

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[1] Morstyn, Farrell, Darby, McCulloch. "Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants" in *Nature Energy*, Vol 3. February 2018.

[2] See https://www.brooklyn.energy/ for details on this program, which is widely recognized as a change-leader.

services (either independently offered by large industrials or bundled by providers) but really entails the surfacing, economic valuing, and transacting of personal consumer preferences. This is able to occur, basically, because of increased availability of data – advanced metering infrastructure (AMIs) and better grid surveillance – and the increased abilities of utilities and retailers to process it. Economic theory forecasts efficiency gains due to this improved preference matching, but there are more profound changes to business models that this paper focuses on.

The combination of DERs and responsive demand brings about a new distribution-level paradigm: the "prosumer" who is well-informed and has the ability to produce and consume power; the "Distributed Energy Resource Management Software" (DERMS) that manages the technicalities associated with the production, and consumption of power on a miniature scale; microgrids that can self-sustain without access to the bulk transmission system, and smart homes that capture the resident's preferences and cost-minimize around them. Such a paradigm imagines real benefits beyond better consumer preference matching: increased resilience to disasters via islanding, avoidance of transmission losses via localized generation[3], and the potential un-commodification of energy as consumers assign value to local and green generation sources.

Accommodating such concepts in the coordinated power system can be challenging. Net metering tariffs and time-of-use rates are straightforward means of capturing some of the benefits that prosumers offer without disrupting the traditional operation and organization of the grid, granting that DER penetration remains low enough. More comprehensive integration has been envisioned, though; Morstyn et al. propose the "Federated Power Plant" (FPP) as the logical combination of the virtual power plant (VPP) and peer-to-peer (P2P) trading networks that have evolved in literature and practice.[4]

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[3] Burger, Jenkins, Huntington, Perez-Arriaga. "Why Distributed? A Critical Review of the Tradeoffs between Centralized and Decentralized Resources" in *IEEE Power and Energy Magazine*, Vol 17. February 2019.
[4] Morstyn et al., 2018.

Under such an arrangement, prosumers dispatch their available generation resources to meet their own demand, and the outside world is represented as another market participant that can buy or sell power and other grid services. The distribution network thus looks like an islanded microgrid from the inside, and like a wholesale VPP from the outside. The complicated software required to actualize this vision is a focus of this paper.

## Smart Homes and Control Algorithms

Households on a microgrid participating in a market framework, whether it involves wholesale transactions mediated by a traditional energy retailer or P2P trading through an FPP, will be controlled by what is known as Demand Side Management (DSM) software, i.e. smart home software. This software attempts to minimize household utility bills by scheduling energy use, taking into account, when applicable, intermittent DER generation and the possibility of load shifting by DER energy storage. Areas of active research include both "deepening" these systems by better incorporating consumer preferences into the optimization and "widening" these systems by optimizing cost over a multitude of networked smart homes through coordination.[5] Research into how exactly DSMs might constructively communicate or what a more centralized clearing platform for microgrids might look like has mushroomed over recent years. Broadly speaking, models range from true P2P bilateral negotiations to centrally solved optimization problems that seek community-wide least cost solutions. (See Zhang et al. for an excellent survey.[6]) What is constant is that the smart home acts as agent in these markets.

Currently operationalized implementations of coordinating DSMs operating on a microgrid through P2P trading are admittedly not so advanced. Several configurations were surveyed in 2018 by

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[5] Alam, St-Hilaire, Kunz. "Peer-to-Peer Energy Trading among Smart Homes" in *Applied Energy*, Vol 238. January 2019.

[6] Zhang, Wu, Zhou, Cheng, Long. "Peer-to-Peer Energy Trading in a Microgrid" in *Applied Energy*, Vol 220. March 2018.

Zhang et al.[7]: Piclo in the UK is a web service where generators can meet consumers; Vendebron in the Netherlands is similar, but credits consumers for injections from their grid-connected DERs; sonnenCommunity in Germany is the most standard with networked users sharing DER-generated energy among themselves and their (sonnenBatterie branded) batteries. That is not to say that more ambitious implementations are not in play. LO3 Energy is a NYC-based startup hoping to deploy a transactive microgrid platform run on blockchain technology. Perth-based Power Ledger aims for something similar.

Within the world of prosumers and smart homes, intermittency is a forever reality. This is intermittency of energy supply, as from solar panel generation or from the alternating presence of an electric vehicle, intermittency of energy demand, as from washing machine schedules and impromptu house-parties, and also the interaction of these two: wildly varying personal utility for the marginal kWh of electricity. The smart home must optimize not only on cost but the "quality of experience" (QoE) of the consumer, as it is described in the literature.[8] Although the DSM software does much to make consumer demand more price elastic, especially as seen in aggregate at the wholesale level, individuals from moment-to-moment will still change their willingness-to-pay (WTP) for the commodity by orders of magnitude. This point becomes salient when considering detection of collusive behavior later in this paper.

Although the literature in DSM and P2P trading is full of research into algorithms to solve such systems and markets, I will shy away from those details in this paper. When describing the proposed experiment below I will gloss agent-based modeling techniques as well as the machine learning algorithms that can power emergent behavior in these agents. These same learning algorithms used in

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[7] Zhang et al., 2018.
[8] Pilloni, Floris, Meloni, Atzori. "Smart Home Energy Management Including Renewable Sources: A QoE-Driven Approach" in *IEEE Transactions on Smart Grid*, Vol 99. September 2016.

an experimental model are actually the same that might be used in a real-world implementation of P2P trading. Besides that, it will be useful only to cover some general facts about algorithms and artificial intelligence to guide the coming discussion on market power and collusion in these systems.

An algorithm is an "explicit, precise, unambiguous, mechanically-executable sequence of elementary instructions"[9]; it is a recipe. What lends the term its powerful air is the computational speed of an algorithm's execution. Machine learning is a process by which a computer internalizes patterns in data (via algorithmic training), from which patterns the computer might then make predictions (via algorithmic execution). Artificial intelligence (AI), although it has many definitions, in this paper will mean more or less the automation of such a system, whereby a system can continually learn from inputs and make updated predictions as outputs. In this framework, a DSM in a smart home is necessarily an AI, connected to various other systems that allow execution (generation, consumption, transaction) on its predictions. But at the core, an AI system is composed of its algorithmic instructions, its phenomenal processor, and its stored data.

## Market Power and Tacit Collusion

A core principle guiding regulation of the electric power sector that has evolved over the past century is that prices to consumers should be fair, that they should be no higher than they need to be to maintain the system.[10] Rate cases, consumer advocates, market monitors, and reams of rules: these are all artifacts of the current liberalized power system meant to protect consumers from rising prices. And among the potential causes of "unfairly" high prices in the wholesale electricity market is the exercise of

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[9] Erickson. Chapter 1 of *Algorithms*. Pre-publication; accessible at http://jeffe.cs.illinois.edu/teaching/algorithms/. Registered with ISBN 978-1-792-64483-3.
[10] Battle, Ocana. Chapter 3 of *Regulation of the Power Sector*, edited by Perez-Arriaga. Published by Springer-Verlag London in 2013.

market power by generation, which has become by now a well known, characterized, and monitored phenomenon.

The bulk power system is prone to market power accumulation by supply firms. Jurisdictions that have not deregulated are characterized by vertically integrated monopolies, and those that have are often littered with geographically correlated remnant firms that may still possess local market power in a system designed to have locally divergent pricing. Barriers to entry by competitor firms are formidable: large capital costs, long lead times, and heavy regulatory burdens accompany new generation (or generation that is changing hands). For traditional metrics of market power, such as the Hirschman-Herfindahl Index, power systems can score worryingly high.[11]

Though same-firm ownership of assets is the common mode of acquiring a high concentration of market power, such a result can come about through other means, like collusion.[12] Collusion implies the willing and secret (because proscribed) coordination between firms on price, and may be made through either explicit or tacit agreement. With successful collusion, multiple firms might act and gain as one, but success here is difficult and unstable. Jacquemin and Slade profile the act of collusion as consisting of agreeing to collude, restraining from cheating, detecting the cheating of others, and punishing of cheating, all of which are quite difficult.[13] Tacit collusion, in which there is no explicit agreement but a stable non-competitive price equilibrium is reached through a series of signals, might also arise and be as effective although it is less stable.[14] The multi-stage prisoner's dilemma game using strategies such as tit-for-tat is an example of this.

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[11] Ventosa, Linares, Perez-Arriaga. Chapter 2 of *Regulation of the Power Sector*, edited by Perez-Arriaga. Published by Springer-Verlag London in 2013.
[12] Jacquemin, Slade. "Chapter 7: Cartels, Collusion, and Horizontal Merger" in *Handbook of Industrial Organization*. Published by Elsevier in 1989.
[13] Ibid.
[14] Beneke, Mackenrodt. "Artificial Intelligence and Collusion" in *International Review of Intellectual Property and Competition Law*, Vol 50. January 2019.

Tacit collusion is more difficult to pull off, but also more difficult to police given the lack of any smoking-gun agreement. On top of this, there is a genuine legal debate about what would constitute tacit collusion anyway: that firms set their prices with full knowledge of other firms' prices is accepted and encouraged behavior. (This is "interdependent pricing".[15]) How interdependent should pricing strategies be allowed to be?

Yet market power *per se* is not necessarily problematic; it does not necessarily lead to higher prices than would be observed in a market where no firm held market power. It is the abuse or exercise of market power that is problematic, and the wholesale power markets have developed precise ways to detect and combat this. Taking the PJM ISO as an example of a well-developed, liberalized wholesale power market, we see a clear method of detection. For every hour that it offers to sell generation into the market, a generator must not only submit its offer curve (to be cleared by the ISO in competitive auction) but also a corresponding cost curve which must represent the marginal cost of each MW offered.[16] (The construction of such a cost curve is intensely regulated, including, for example, the filing of an algorithmic "fuel cost policy" with the PJM Market Monitor.[17]) Given the incentives inherent in PJM's market clearing structure, the hourly energy clearing price should not deviate significantly from the marginal cost of the marginal generator, which is the competitive outcome.[18] Since PJM knows both the clearing price and the marginal costs of all generators, this is an easy signal to detect.

Furthermore, the PJM Market Monitor, tasked partly with surveilling for anti-competitive behavior, has a well developed "Three Pivotal Supplier" test that can prevent exercise of market power before it is even attempted. The intuition is that if, on any given hour, a supplier is *calculated* to be able to influence the auction clearing price, it is disallowed from offering anything other than its marginal

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[15] Beneke, Mackenrodt, 2019.
[16] PJM. "Manual 11: Energy & Ancillary Services Market Operations", Revision 105. April 2019.
[17] PJM. "Manual 15: Cost Development Guidelines", Revision 31. February 2019.
[18] Jacquemin, Slade, 1989.

cost (plus a small adder). This detail is only to say that the exercise of market power is a solved problem in wholesale power markets, or as nearly as possible given the oligopolistic nature of them.

## Motivation

Stepping back now into the world of DERs, microgrids, VPPs, P2P trading, and AI-controlled smart homes, I propose that the exercise of market power is not a solved problem. It might, in fact, become an undetectable issue that leads to widespread higher prices for consumers. There are three logical steps in the argument:

1. There are technical reasons why an AI-driven P2P trading system might overcome traditional impediments to successful collusion.
2. The effective accumulation of market power then becomes a possibility despite what seems, at first sight, an extremely fragmented marketplace resistant to oligopoly.
3. The notion of "marginal cost" differs between the DER-outfitted prosumer and the traditional utility-scale generator as suppliers of power, which I hypothesize makes exercise of this effective market power potentially undetectable and unpoliceable.

The first of these steps (to take them in turn) is already established in the literature. Algorithmic pricing is the "'talk of the town' in the European competition law community", which has promoted itself as a leader in the regulation of digital and online activity.[19] Once it has been granted that AI-empowered agents are charged with handling transactions – as the case of our P2P trading network – it is evident that tacit collusion could occur in principle: the basic pre-requisites of signaling and agency are met.  But whereas tacit collusion has before seemed unstable in all but the most concentrated of markets, algorithms stabilize, via high availability of information, high processing speed, and calculated

[19] Ezrachi, Stucke. "Sustainable and Unchallenged Algorithmic Tacit Collusion", University of Tennessee Legal Studies Research Paper No. 366 and Oxford Legal Studies Research Paper No 16. November 2018.

objectiveness, fragmented markets.[20] Since the high-level impediment to tacit collusion is uncertainty around an opponent's price reaction, and since AI effectively (through automated machine learning) "lowers the cost of solving uncertainty" in terms of both time and money, tacit collusion becomes much more feasible in theory.[21]

On the second point it becomes plausible to imagine scenarios on a P2P trading network where agents achieve periods – however brief – of anti-competitive equilibrium with heightened prices, brought about by lightning quick signaling, processing, and comparison to previous "rounds in the game".

The third step accentuates the theoretical risk of collusion on the microgrid, and has not been raised yet in the literature. From Pilloni et al.'s notion of "Quality of Experience"[22] for the prosumer, I have already noted that the prosumer's WTP for power (and thus the opportunity cost of DER power sold) changes greatly from moment to moment. Moreover, the QoE as a determinant of WTP/opportunity cost is both a significant driver and is subjective to a specific person and time; it is distinctly *unlike* the algorithmic and reproducible fuel cost policy that a wholesale generator must use to price its fuel inputs. Having said above that the power system's (PJM's) main defense against the exercise of market power is full and accurate knowledge of a supplier's marginal costs, there is no existing defense against colluding prosumers offering to sell power since their costs are unknown and unknowable. Such a risk of undetectable market power exercise might occur intra-microgrid, i.e. groups of net-selling prosumers collude to raise prices for net-buying prosumers, and inter-microgrid, i.e. the aggregate microgrid represented as a VPP to the wholesale market – without cost scrutiny – could exercise local market power or collude with their VPPs for more global exercise.

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[20] Ibid.
[21] Beneke, Mackenrodt, 2019.
[22] Pilloni et al., 2016.

## Proposed Investigation

The goal of the proposed investigation is to show the possibility of collusive behavior between AI-enabled smart home agents trading energy on a microgrid, and not necessarily to show how likely such a result may be. To accomplish the simulation, a scenario or configuration must first be chosen to establish the scope and specifics of the market being studied. Next, exogenous variables like the weather (to determine load and solar generation) and fuel prices (if power is available to import from elsewhere on the grid) must be specified. Finally, the smart homes (agents) themselves must be instantiated and modeled in a way that might lead to recognizable, real-world dynamics. Of these three steps, the scenario choice and agent instantiation deserve further treatment.

### Scenarios

The scenario choice dictates how to simulate and pressure-test the mock microgrid. For the construction of the scenarios I lean on Morstyn et al.'s review of likely future microgrid configurations.[23] Some of the more technical elements of power systems, like frequency control, will be excluded from the analysis, as I am interested only in the price formation around energy.

Scenario 1 considers a fully bilateral P2P trading solution. In this, the most decentralized scenario, each agent continuously publishes bids and offers for energy to other agents directly in order to maximize its own utility. The agents may each be endowed with different DER combinations, demand schedules, price elasticities, etc. Alam et al. consider algorithms that converge for such a market.[24]

Scenario 2 considers a microgrid controlled by a distribution system operator (DSO) that coordinates dispatch among all connected agents in a central manner. This is analogous to the

[23] Morstyn et al., 2018.
[24] Alam et al., 2019.

coordination of the bulk grid by ISOs, although the exact manner of dispatch need not be the same. Zhang et al., for example, propose an "ElecBay" as a sort of communal shopfront in which buyers submit blind bids for products (e.g. energy in the next hour).[25] The highest bidder gets the product after a system security check. Whatever the method, the core feature of this scenario is that agent preferences, transmitted as prices, are collected centrally by an operator.

Scenario 3 considers a microgrid from outside, as it appears on the bulk grid to the traditional ISO as a VPP. This is essentially the full FPP model proposed by Morstyn et al. as a realizable outcome, though during simulation the intra-microgrid dynamics could be abstracted away.[26]

## Agents

The simulation should include independent agents that mimic as closely as possible the real thing. Since the "real thing" in this case is in fact just other algorithms, the agents in my model should be the same as agents that would be deployed in the real world. This can be accomplished with a class of models known as Agent Based Models (ABM).

The core intuition for the ABM is that it models each agent as a discrete decision-maker that is able to make decisions over the course of a simulation according to the market rules and any information it has access to. By creating many such agents with varied attributes and preferences and allowing them to interact, it is possible to generate believable and intuitive market-level patterns. The ABM has been used before to study structural changes in energy and capacity markets, recently by Hach and Spinler, who applied one to the UK energy market.[27]

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[25] Zhang et al., 2018.
[26] Morstyn et al., 2018.
[27] Hach, Spinler. "Robustness of Capacity and Energy-Only Markets - A Stochastic Dynamic Capacity Investment Model" in *SSRN*. October 2014.

It is important to make a note here about the type of modelling that this paper attempts: it is not to predict the future but rather to consider what could occur in the future and how those situations might arise. To do anything else when considering a dynamic problem like this, as Herbert Simon reminds us, would be useless.[28] Accordingly this paper treats the modelling much like a system dynamics problem, not intended for much more than identifying modes of behavior.

An important component to agent-based modelling beyond the very elementary type is to allow strategic behavior and learning by agents. This can range from the very simple – for example the agents deployed by Staudt et al that are able to change a single offer price parameter every several iterations of the simulation[29] – to the very complex – for example the type of learning exhibited by Deepmind's AlphaGo when playing Go.[30] An intermediate complexity learning algorithm termed "Q-Learning" is appropriate to use in this investigation because it is general enough to handle the quite huge expected parameter space of the simulation (and so a function approximation algorithm would likely be implemented), still simple to implement, and also has already been shown to power market collusion simulations.[31]

## Evaluation

The simulation once implemented will only be useful if key diagnostic variables are monitored underway. The goal of the investigation, again, is to identify collusive behavior if it arises. Since the key outcome from the exercise of supply-side market power (whether via collusion or not) is elevated

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[28] Simon. "Prediction and Prescription in Systems Modeling" in *Operations Research*, Vol 38, 1. 1990.
[29] Staudt, Garttner, Weinhardt. "Assessment of Market Power in Local Electricity Markets with Regards to Competition and Tacit Collusion" in conference proceedings for *Multikonferenz Wirtschaftsinformatik*. March 2018.
[30] Silver, Schrittwieser, Simonyan, Antongolou, Huang, Guez, Hubert, Baker, Lai, Bolton, Chen, Lillicrap, Hui, Sifre, van den Driessche, Graepel, Hassabis. "Mastering the Game of Go without Human Knowledge" in *Nature*, Vol 550. October 2017.
[31] Klein. "Autonomous Algorithmic Collusion: Q-Learning Under Sequential Pricing", *Amsterdam Center for Law & Economics* Working Paper No. 2018-05. January 2019.

pricing, the energy prices must be tracked meticulously in the simulation. And since the only way to know if the tracked energy prices are elevated is to compare them to marginal costs, these must also be tracked, and for each agent individually. These two time series should capture all the information necessary to establish collusion between agents.[32]

## Policy Discussion

The heightened risk of collusive behavior in digitized marketplaces in general is a serious regulatory and policy issue, and it is perhaps more serious in the distributed power system given the opacity around marginal costs presented above.

The most troubling question for markets in general is that tacit collusion blurs the line between acceptable interdependent pricing strategies that ultimately yield pro-consumer outcomes (e.g. price wars) and unacceptable interdependent pricing strategies that give anti-consumer outcomes (e.g. collusive price fixing). Algorithmic pricing only magnifies this problem, both granting bona fide efficiencies and increasing the risk of price exploitation. Thus any attempt at regulation must be wary to sift the good from the bad; indiscriminate outlawing of “mere interdependence” in pricing strategies would do much more harm than good.[33] Perhaps the most consequential question from the competition law arena is whether the concept of “agreement” itself is becoming an outdated notion.[34]

Against this broader picture of angst, there have been many useful suggestions for combatting tacit collusion on a smaller scale. I categorize them into three categories: legal treatment adaptation, technical solutions, and market rule changes. First, legal suggestions center either on shifting the focus of scrutiny from communications between agents to the prices directly, or on shifting the burden of

[32] Beneke, Mackenrodt, 2019.
[33] Ibid.
[34] Ezrachi, Stucke, 2018.

proof from the prosecution (showing positively that there was collusion) to the defense (showing negatively that there was not collusion).[35] Second, there is hope that technical advances in machine learning, such as ongoing work in interpretability, might effectively solve the problem; algorithms would explain in natural language rationales for their behavior, which could easily be checked for compliance.

The third category, market rule changes, is most interesting because the solutions could conceivably be specified to the power industry and microgrids. One set of suggestions attempts to hamstring algorithms either by reducing the frequency of with which they can change prices, or by reducing the extent to which they can observe other agents' prices.[36] The obvious friction here is that indiscriminately battling interdependent price strategies might dampen competitive efficiencies; an inflection point must be found in this rate-limiting approach, then, where most collusive behavior is prevented but efficiency improving behavior is left untouched. Empirical studies and calibration would be needed on a market-by-market basis. A benefit of this approach is that it is straightforward (technically speaking) to implement and police.

A second set of market rule solutions involves retrospective market analysis, of the type frequently performed by PJM's Market Monitor, for example. Ezrachi and Stucke have proposed an "algorithmic pricing incubator"[37] – essentially a simulation sandbox not far different from what I proposed in the experiment above – that would be run alongside a market. Using the same inputs – topology, weather, real input prices – the monitoring unit could assess pricing outcomes under a variety of controlled scenarios. If the real world observed pricing outcome is higher than a simulated

[35] Ibid.
[36] Beneke, Mackenrodt, 2019.
[37] Ezrachi, Stucke, 2018.

competitive outcome, a more in-depth investigation could be launched. This approach of "fighting fire with fire" overcomes some of the inherent difficulties faced when dealing with AI "black boxes".[38]

Translating the first set of suggestions – rate-limiting and information-shielding – to the power market is straight forward, and it would be a simple solution to the P2P tacit-collusion problem if it worked. Guaranteeing that benefits (reduced collusion) exceed costs (reduced efficiencies) may be impossible, however. The implementation of a pricing incubator by an Independent Market Monitor would be interesting, but only to the extent that each prosumer's QoE/opportunity costs could be measured and simulated with some degree of accuracy. Even with highly-specified cost guidelines, such as are maintained for wholesale generators in PJM's Manual 15, the problem of falsified or spoofed preferences to artificially control marginal costs seems all too easy. This phenomena could derail any meaningful attempt at simulated comparisons of prices.

Two structural hopes for competitive outcomes in a microgrid remain, depending on the level of centralization involved. In a relatively centralized system, the technical constraints of maintaining balance of supply and demand and providing for contingencies on the system are met by Independent System Operators that, among many other processes, determine energy clearing prices. The microgrid equivalent, the Distribution System Operator, might attempt to implement some collusion-resistant auction mechanisms that have been proposed in literature.[39] Although such mechanisms do involve manipulation of information access, the details may be easier to implement centrally at the market access point than to distribute such limitations among the agents.

In a relatively decentralized system where grid services are cleared fully bilaterally, or where only ancillary and stability services are cleared in a central manner, the above approach will not work.

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[38] Beneke, Mackenrodt, 2019.

[39] Che, Kim. "Optimal Collusion-Proof Auctions" in *Journal of Economic Theory*, Vol 144. March 2009.

However, recognizing that not only the net-selling prosumers but also the net-buying prosumers are controlled by AI, we might envision that any attempts at sell-side collusion might quickly founder due to price signaling or responsive collusion from the buy-side. This is to say that, although AI firms might be able to tacitly collude in a traditional marketplace, in the AI marketplace they are matched to equal opponents. This notion is explored somewhat in Gal.[40]

## Conclusion

I should stress that while the subject of this paper lies decidedly in the future, the topic (tacit collusion by AI-controlled P2P trading smart homes) is not merely hypothetical. It is not doubtful that microgrids with transactive services determined by smart homes will appear at some point. That this is in the future allows time for some of the easier solutions, such as technical improvements in algorithm interpretability, to come to fruition. Work on this problem should begin now, however. A "proactive shaping of industry behavior through dialogue with stakeholders, targeted regulation, and norm generation"[41] is likely to generate the best outcomes.

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[40] Gal. "Algorithms as Illegal Agreements" in *Berkeley Technology Law Journal*. Forthcoming.
[41] Mehra. "Antitrust and the Robo-Seller: Competition in the Time of Algorithms" in *Minnesota Law Review*, Vol 100. Forthcoming.

# Bibliography


1. Alam, St-Hilaire, Kunz. "Peer-to-Peer Energy Trading among Smart Homes" in *Applied Energy*, Vol 238. January 2019.
2. Battle, Ocana. Chapter 3 of *Regulation of the Power Sector*, edited by Perez-Arriaga. Published by Springer-Verlag London in 2013.
3. Beneke, Mackenrodt. "Artificial Intelligence and Collusion" in *International Review of Intellectual Property and Competition Law*, Vol 50. January 2019.
4. Burger, Jenkins, Huntington, Perez-Arriaga. "Why Distributed? A Critical Review of the Tradeoffs between Centralized and Decentralized Resources" in *IEEE Power and Energy Magazine*, Vol 17. February 2019.
5. Che, Kim. "Optimal Collusion-Proof Auctions" in *Journal of Economic Theory*, Vol 144. March 2009.
6. Erickson. Chapter 1 of *Algorithms*. Pre-publication; accessible at http://jeffe.cs.illinois.edu/teaching/algorithms/. Registered with ISBN 978-1-792-64483-3.
7. Ezrachi, Stucke. "Sustainable and Unchallenged Algorithmic Tacit Collusion", University of Tennessee Legal Studies Research Paper No. 366 and Oxford Legal Studies Research Paper No 16. November 2018.
8. Gal. "Algorithms as Illegal Agreements" in *Berkeley Technology Law Journal*. Forthcoming.
9. Hach, Spinler. "Robustness of Capacity and Energy-Only Markets - A Stochastic Dynamic Capacity Investment Model" in *SSRN*. October 2014.
10. Jacquemin, Slade. "Chapter 7: Cartels, Collusion, and Horizontal Merger" in *Handbook of Industrial Organization*. Published by Elsevier in 1989.
11. Klein. "Autonomous Algorithmic Collusion: Q-Learning Under Sequential Pricing", *Amsterdam Center for Law & Economics* Working Paper No. 2018-05. January 2019.
12. Mehra. "Antitrust and the Robo-Seller: Competition in the Time of Algorithms" in *Minnesota Law Review*, Vol 100. Forthcoming.
13. Morstyn, Farrell, Darby, McCulloch. "Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants" in *Nature Energy*, Vol 3. February 2018.
14. Pilloni, Floris, Meloni, Atzori. "Smart Home Energy Management Including Renewable Sources: A QoE-Driven Approach" in *IEEE Transactions on Smart Grid*, Vol 99. September 2016.
15. PJM. "Manual 11: Energy & Ancillary Services Market Operations", Revision 105. April 2019.
16. PJM. "Manual 15: Cost Development Guidelines", Revision 31. February 2019.
17. Silver, Schrittwieser, Simonyan, Antongolou, Huang, Guez, Hubert, Baker, Lai, Bolton, Chen, Lillicrap, Hui, Sifre, van den Driessche, Graepel, Hassabis. "Mastering the Game of Go without Human Knowledge" in *Nature*, Vol 550. October 2017.
18. Simon. "Prediction and Prescription in Systems Modeling" in *Operations Research*, Vol 38, 1. 1990.
19. Staudt, Garttner, Weinhardt. "Assessment of Market Power in Local Electricity Markets with Regards to Competition and Tacit Collusion" in conference proceedings for *Multikonferenz Wirtschaftsinformatik*. March 2018.
20. Ventosa, Linares, Perez-Arriaga. Chapter 2 of *Regulation of the Power Sector*, edited by Perez-Arriaga. Published by Springer-Verlag London in 2013.
21. Zhang, Wu, Zhou, Cheng, Long. "Peer-to-Peer Energy Trading in a Microgrid" in *Applied Energy*, Vol 220. March 2018.