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INTRODUCCIÓN EDITORIAL

Nuevos modelos de negocio en el sector energético

Hay tres elementos que, si bien se han venido desarrollando durante los últimos años, están llegando a un nivel en el que prometen cambiar de manera profunda el sistema energético que conocemos. Su llegada a la madurez viene mediada en todos ellos por el desarrollo tecnológico. Un desarrollo que permite activar a los consumidores eléctricos en los países desarrollados, que está facilitando el acceso a la energía en países en desarrollo, y que permite que el *tight oil* inunde los mercados de petróleo.

Esto a su vez está abriendo nuevos mercados, o transformando radicalmente los existentes. La activación del consumidor cambia el balance en los mercados eléctricos, en el fondo aproximándolos a lo que sucede en otros mercados, en los que es el cliente –la demanda– el que dirige al mercado. La posibilidad de dar acceso a la energía a los más de 1.200 millones de personas que no lo tienen, además de corregir una grave injusticia social, crea un mercado de más de 48.000 millones de dólares anuales. Finalmente, la competitividad del *tight oil* está cambiando radicalmente la estructura productiva del mercado del petróleo, y con ello los jugadores principales, así como sus implicaciones económicas y geopolíticas.

Ante estos cambios disruptivos, las empresas se ven obligadas a replantear su estrategia para sobrevivir. Deben encontrar nuevos modelos de negocio que encajen en esta nueva situación, si quieren seguir manteniéndose en el mercado ante la pujanza de nuevos agentes. Y deben tener visión de largo plazo para anticiparse a las posibles disrupciones.

Sin embargo, para que todos estos cambios de paradigma tengan lugar en mercados altamente regulados como el sector eléctrico, es imprescindible un cambio en el marco actual, que permita que las nuevas tecnologías y comportamientos jueguen en un terreno equilibrado, evitando de esta forma tanto el mantenimiento ineficiente del *statu quo* como la introducción precipitada de las nuevas tecnologías, y propiciando esa destrucción creativa que propugnaba Schumpeter como motor del desarrollo humano.

En este número de *Papeles de Energía,* los mayores expertos mundiales de estos temas (algunos de ellos españoles) nos ofrecen su análisis sobre las oportunidades de negocio y los cambios de regulación que se están planteando tanto en los mercados eléctricos maduros, como en los países en desarrollo, como en el mercado del petróleo.

Tomás Gómez y **José Pablo Chaves**, profesor e investigador respectivamente del Instituto de Investigación Tecnológica (IIT) de la Universidad Pontificia Comillas, resumen los principales mensajes del estudio *Utility of the Future*, realizado por el MIT y el IIT. El mensaje principal es que, en un contexto de avance de las nuevas tecnologías de generación y almacenamiento distribuidos, y de mayor participación del consumidor, es imprescindible transformar el actual sistema de determinación de precios y cargos de electricidad. Y es que la estructura actual de precios y cargos, generalmente basada en tarifas volumétricas (es decir, basadas en el consumo de energía) es demasiado simple para capturar las diferencias locales y temporales de valor de los recursos distribuidos, y por tanto no permite establecer un terreno de juego nivelado entre estos recursos y los recursos centralizados tradicionales. Los autores también detallan las distintas contribuciones que pueden aportar estos recursos al sistema, y proponen una serie de recomendaciones regulatorias dirigidas a ponerlas en valor, de forma no discriminatoria y tecnológicamente neutra. Este cambio regulatorio permitirá una activación más eficiente de estos recursos, al enviar las señales económicas adecuadas, y con ello una transformación potencial de la estructura del sector eléctrico.

En segundo lugar, **Ignacio J. Pérez-Arriaga**, profesor de la Universidad Pontificia de Comillas y del MIT, nos presenta las posibilidades de regulación y de modelos de negocio que existen para facilitar el acceso a la energía en los países en desarrollo. Su artículo defiende que todavía es necesario diseñar una regulación sólida, y un conjunto de modelos de negocio atractivos, que permitan desbloquear el acceso a la energía a la población que no cuenta con él. Y que para ello no podemos acudir a los criterios habituales de la regulación eléctrica en países maduros. Hace falta regulación creativa que, teniendo en cuenta las características específicas de estos países, cierre la brecha económica a la que se enfrenta la electrificación; así como una planificación de largo plazo que permita optimizar los escasos recursos para ello. Por otro lado, los modelos de negocio deben aprovechar los desarrollos tecnológicos tanto de la extensión de red como de los sistemas aislados, ambos necesarios; ser lo suficientemente flexibles como para poder evolucionar en paralelo al aumento de demanda de los clientes; y tener en cuenta las interacciones con la provisión de otros servicios básicos para el desarrollo, como el agua, la educación o la salud. El profesor Pérez-Arriaga considera que este es el momento adecuado para impulsar estos cambios desde las grandes empresas energéticas, en colaboración con las iniciativas locales.

Por último, **Lutz Kilian**, profesor de la Universidad de Michigan, y uno de los mayores expertos mundiales en el tema, analiza para nosotros las consecuencias que el auge del *tight oil* tiene en los precios del petróleo, y también la sostenibilidad de este modelo de negocio. Su artículo ofrece varias consideraciones muy interesantes respecto a la fragmentación temporal del mercado global del petróleo, sobre las razones del embargo a la exportación de petróleo desde EE.UU. o sobre la competitividad del refino en EE.UU. Kilian concluye que la bajada de los precios globales del petróleo causada por el *tight oil* es actualmente reducida y que se debe más bien a la reducción de la demanda. Además, nos muestra cómo el efecto de la bajada de precios en la economía estadounidense también ha sido muy reducido, al estar mitigado por la reducción en la inversión en el sector del petróleo. Finalmente, Kilian señala que se ha reducido la sensibilidad a los precios de la inversión en el sector petrolífero y analiza la distinta sensibilidad a estos precios de la inversión en *tight oil* comparada con la inversión en petróleo convencional.

En todo caso, los tres artículos aportan muchas más ideas de interés que no pueden resumirse en esta breve introducción, por lo que animo a todos los lectores a estudiarlos con detenimiento. Los análisis presentados nos muestran cómo puede ser el futuro del sector energético, y conviene estar preparados para ello.

Los precios y cargos regulados de electricidad ante un futuro con recursos distribuidos y consumidores activos*

Tomás Gómez y José Pablo Chaves[1]

Resumen

El pasado mes de diciembre de 2016 se publicó el estudio *Utility of the Future* realizado por el Massachussets Institute of Technology (MIT) en colaboración con el Instituto de Investigación Tecnológica de la Universidad Pontificia Comillas (Pérez-Arriaga *et al.*, 2016). Una de las principales recomendaciones de este estudio es la necesidad de revisar el actual sistema de precios y cargos regulados que experimentan los consumidores de electricidad. Las nuevas tecnologías de generación y almacenamiento distribuidos –junto con el papel más activo de los consumidores adoptando sus propios recursos para producir, almacenar, y gestionar energía– están cambiando el paradigma de los sistemas eléctricos. Ante esta nueva realidad y en aras de la eficiencia, se concluye que el actual sistema de precios y cargos de electricidad debe sufrir una trascendental transformación. En este artículo se profundiza en esta recomendación describiendo en detalle los elementos que la conforman y dando pautas claras a los reguladores y gobiernos para abordar la necesaria reforma.

Palabras clave: Sistemas eléctricos, recursos distribuidos, tarifas.

INTRODUCCIÓN

La creciente presencia de recursos distribuidos de energía de pequeña y mediana escala conectados directamente a las redes de distribución de electricidad o a través de las instalaciones de los consumidores, se inscribe parcialmente en la tendencia general hacia un modelo energético de bajas emisiones en carbono, y podría conducir a un cambio de paradigma en el sistema eléctrico. Entre estos

* Las ideas y recomendaciones expresadas en este artículo surgieron fruto del trabajo colaborativo realizado en el seno del proyecto *Utility of the Future* dirigido por el Prof. Ignacio Pérez-Arriaga. Los autores también agradecen las contribuciones de los otros componentes del equipo de trabajo y en especial de Carlos Batlle, Pablo Rodilla, Claudio Vergara, Jesse Jenkins, Ashwini Bharatkumar y Scott Burger.

1 Instituto de Investigación Tecnológica (IIT) de la Universidad Pontificia de Comillas.

recursos se encuentran la generación distribuida solar, eólica, microturbinas de diferentes tipos, microcogeneración, tecnologías termoeléctricas como bombas de calor, el almacenamiento mediante baterías, dispositivos que reúnen características de demanda, generación y almacenamiento, como los coches eléctricos, y las tecnologías de la información y las comunicaciones que permiten una gestión más inteligente de las redes y usuarios conectados a ellas. La pregunta de hasta qué punto el sistema tradicional basado en grandes centrales va a continuar siendo el prevalente en las próximas décadas y cuál es el papel que van a jugar los recursos distribuidos adquiere total relevancia en este contexto.

Se pueden identificar diferentes impulsores de este cambio. En primer lugar, el desarrollo y la innovación tecnológica están reduciendo el coste de la generación renovable, como la solar fotovoltaica y eólica, del almacenamiento de energía, baterías de ion-Litio y almacenamiento térmico por medio de tecnologías como bombas de calor. En segundo lugar, las políticas de promoción de las energías renovables están facilitando la instalación de volúmenes importantes de dichas tecnologías, lo que a su vez propicia la reducción de costes. Finalmente, los consumidores de electricidad están comportándose de forma más activa en el mercado, tomando decisiones con respecto a la forma más económica y adecuada de gestionar su consumo, convirtiéndose en consumidores activos e incluso participando en la provisión de servicios en el mercado eléctrico.

Existen claras evidencias de que este potencial cambio de paradigma y los cambios regulatorios que lleva aparejados empiezan a ser objeto de atención entre los reguladores energéticos de muchos países. Como ejemplo sirvan el reciente informe publicado por la asociación de las comisiones reguladoras en Estados Unidos (NARUC, 2016) y el paquete de invierno de propuestas legislativas hecho público por la Comisión Europea el pasado mes de noviembre y que lleva por lema “Nuevas reglas para una transición energética centrada en el consumidor” (Comisión Europea, 2016).

Los precios y cargos que pagan actualmente los consumidores en la factura eléctrica en la mayoría de los países resultan inadecuados para conseguir una transición eficiente, donde tanto los recursos tradicionales centralizados como los nuevos recursos distribuidos puedan competir en igualdad de condiciones proveyendo los servicios demandados. Por lo general los métodos utilizados hasta ahora por los reguladores para transmitir los precios del mercado o asignar los costes de las actividades reguladas y otros cargos son demasiado simples para capturar las diferencias temporales y locales en el valor de la electricidad y de los servicios asociados. Por ejemplo, el uso de unas tarifas fijas volumétricas por kWh no permite reconocer el valor cambiante de la energía eléctrica a lo largo del día y por tanto anula el posible modelo de negocio asociado a que el consumidor disponga de mecanismos de gestión de la demanda para disminuir su consumo en horas de precios altos y aumentarlo en horas de precios bajos.

En el contexto actual donde los consumidores tienen multitud de opciones tecnológicas para cubrir sus necesidades energéticas e incluso para proveer servicios al sistema, la necesidad de desarrollar un sistema eficiente de precios y cargos se convierte en una prioridad. Este sistema, siguiendo la analogía del sistema nervioso humano, debe llegar a todos los rincones, incluidos los consumidores residenciales. De esta forma, las decisiones de inversión y operación en recursos distribuidos tomadas por los consumidores para su propio beneficio o confort conducirán al aumento de la eficiencia global del sistema eléctrico, promoviendo además la competencia efectiva entre recursos centralizados y distribuidos.

En este artículo se presentan los principios generales y los diferentes ingredientes del sistema de precios y cargos propuesto, en el contexto de un futuro con mayor presencia de recursos distribuidos para conseguir un sistema eléctrico eficiente. Este sistema eficiente de precios y cargos permitirá crear un marco equilibrado para que los recursos centralizados y distribuidos puedan aportar valor al sistema eléctrico a través de la prestación de servicios, los cuales se describirán en la siguiente sección. Finalmente se presenta un decálogo de recomendaciones que proporciona pautas claras y ordenadas a seguir por los reguladores para su progresiva implementación.

EL VALOR DE LOS RECURSOS ENERGÉTICOS

El valor de los recursos energéticos, tanto centralizados como distribuidos, puede asociarse a una serie de beneficios que pueden clasificarse en dos tipos. El primero son los beneficios que se generan cuando dichos recursos proveen servicios a los consumidores o dan servicios de apoyo al sistema eléctrico necesarios para su buen funcionamiento. El segundo son otros beneficios que van más allá del sistema eléctrico.

Además, los beneficios que aportan los recursos energéticos tienen una componente geográfica y temporal, es decir, dependen del lugar y del momento en los que se presten los servicios asociados. La componente geográfica o local, al estar conectados cerca de los consumidores, y a las redes de distribución, es lo que constituye el valor diferencial de los recursos distribuidos y de lo que carecen, por el contrario, los recursos centralizados.

Existe una amplia gama de servicios que tanto los recursos centralizados como los distribuidos pueden proveer al sistema eléctrico. La clasificación de los servicios propuesta en este estudio intenta ser generalizable para la mayoría de contextos regulatorios, mercados y tecnologías.

El principal servicio para el consumidor final es la energía eléctrica que se usa para distintos propósitos (iluminación, funcionamiento de aparatos eléctricos, etcétera). La energía puede ser abastecida tanto mediante recursos distribuidos como mediante recursos centralizados, y tiene un marcado carácter local dependiendo del nudo de la red donde se provea o consuma. Sin embargo, hay otros servicios, por ejemplo la reserva de potencia necesaria para mantener el control de la frecuencia del sistema, donde los recursos distribuidos también pueden cooperar pero donde no aportan un valor diferencial con respecto a los centralizados. El cuadro 1 resume los principales beneficios que aportan los recursos eléctricos, según los servicios que proveen.

Los recursos distribuidos pueden proveer valor para el sistema eléctrico dependiendo de su ubicación, como la reducción de pérdidas óhmicas y congestiones en las redes eléctricas (por límites térmicos o tensión). Por ejemplo, al instalar generación distribuida en el mismo punto de conexión que la demanda los flujos por las redes pueden disminuir y con ellos las pérdidas asociadas al transporte de energía. Sin embargo, hay que recordar lo que se conoce como beneficios marginales decrecientes, esto es, cuanta más generación distribuida se instale, su bene-

Cuadro 1
Clasificación del valor de los recursos distribuidos y centralizados

	Valor asociado a la ubicación	Valor independiente de la ubicación
Valor para el sistema eléctrico	Energía	Capacidad firme
	Margen de capacidad de redes	Reservas de potencia para control de frecuencia
	Calidad de suministro	Cobertura ante variabilidad del precio
	Fiabilidad y resiliencia	
Otros valores	Uso del espacio	Reducción de emisiones
	Empleo local	Seguridad de suministro energético

ficio en reducción de pérdidas irá disminuyendo y, en todo caso, dependerá de la alineación que exista entre el consumo local y la generación local. Si la generación local supera al consumo local y como consecuencia se exporta energía hacia el resto del sistema, las pérdidas podrían volver a aumentar por el incremento de flujo en la red. Siguiendo la misma lógica, el uso de recursos distribuidos podría aliviar problemas de congestión en la red cambiando el perfil de la generación local o del consumo local y, de esta manera, las inversiones en los activos de redes se podrían evitar o retrasar. De nuevo, este efecto dependerá del nivel de penetración de dichos recursos. Inicialmente las inversiones en elementos de red necesarias para transportar energía y mantener la calidad del suministro se pueden evitar, pero si todos los consumidores en una determinada localidad empiezan a instalar generación distribuida, podría darse el efecto contrario teniéndose que reforzar la red para poder evacuar la energía en las horas de la punta de generación.

Además, los recursos distribuidos, al estar cerca de la demanda, pueden tener un valor en términos de mejoras en la calidad y fiabilidad del suministro eléctrico. Ante un posible corte de suministro, un generador local puede satisfacer la demanda local mejorando así la calidad del suministro. De igual manera, ante catástrofes naturales que provoquen caídas en el tendido eléctrico la generación local puede aumentar la resiliencia del sistema suministrando energía en estas situaciones de emergencia.

Los recursos distribuidos y centralizados pueden también proveer otros servicios al sistema eléctrico que por lo general no dependen de la ubicación del punto de conexión donde se intercambia energía con el sistema, como por ejemplo el servicio de reserva de potencia para controlar la frecuencia del sistema eléctrico ante desequilibrios instantáneos entre generación y demanda.

En esta misma línea, también, los recursos centralizados y distribuidos pueden contribuir a asegurar capacidad firme de generación para hacer frente a eventos que amenacen la seguridad de suministro o servir como cobertura ante la variabilidad de los precios de la electricidad en los mercados mayoristas. Estos servicios tienen un valor que, por lo general, es igual para todo el sistema eléctrico interconectado, independientemente de la ubicación específica de los recursos.

Como se muestra en el cuadro 1, hay beneficios locales asociados a los recursos distribuidos que van más allá del sistema eléctrico. Por ejemplo, una posible mejora en el uso del espacio/terreno, principalmente en lugares donde el espacio es limitado o tiene mucho valor, como en las ciudades. Un claro ejemplo de este valor es la instalación de placas fotovoltaicas en los tejados. Adicionalmente, la instalación de recursos distribuidos también podría tener un efecto en aumentar el empleo local, aunque la estimación de este efecto es mucho más compleja. Finalmente, hay valores para los consumidores que van más allá de lo meramente económico. Algunos consumidores podrían obtener cierto valor o satisfacción al autogenerar su electricidad con energía verde, por ejemplo, a pesar de que ello pueda resultar más costoso que la alternativa de comprar directamente la energía de la red.

Finalmente, otros beneficios independientes de la ubicación de los recursos que también se incluyen en el cuadro 1 son la reducción de emisiones de gases de efecto invernadero, cuando la generación sea de origen renovable (independientemente de su ubicación) o mediante reducción u optimización del consumo a través de medidas de gestión de la demanda o eficiencia energética. Además, la generación renovable tiene beneficios en la seguridad de suministro energético al ser un recurso local que no depende de factores externos.

TARIFAS VOLUMÉTRICAS Y BALANCE NETO DE ENERGÍA COMO PROMOCIÓN DE LA GENERACIÓN RENOVABLE UBICADA EN LAS INSTALACIONES DE LOS CONSUMIDORES

Los consumidores de electricidad reciben señales económicas en forma de precios y cargos que conforman la tarifa eléctrica. Dependiendo del nivel de evolución del mercado, estas señales se encuentran más o menos desagregadas de acuerdo a los diferentes conceptos que involucran. Por ejemplo, los consumidores en mercados con competencia a nivel mayorista y minorista, pueden elegir su suministrador negociando libremente un precio para la energía en el formato que más les convenga, y deben pagar adicionalmente una tarifa que comprende el coste de las redes de transporte y distribución y también puede incluir otros costes regulados que denominaremos de política energética u otras políticas y que incluyen por ejemplo subsidios a las energías renovables, ayudas sociales para consumidores vulnerables, o compensaciones para regiones insulares, entre otros.

En general, aunque los grandes consumidores pueden participar directamente en el mercado mayorista y en algunos casos participar también en la provisión de servicios de sistema, por ejemplo reserva de potencia para el control de la frecuencia, lo normal es que los consumidores reciban precios y tarifas con una discriminación temporal muy limitada, en algunos casos con diferentes períodos tarifarios en el día y año (tarifas de uso), y con prácticamente ninguna señal de discriminación local (a veces se diferencian los cargos de redes por el nivel de tensión donde se conecta el consumidor en la red).

En el contexto actual y futuro de consumidores activos con capacidad para instalar sus propios recursos de generación y con alternativas de consumo más eficientes, la práctica de tarifas volumétricas crea una serie de problemas de eficiencia económica en la recuperación de los costes regulados.

El problema de recuperación de costes se ve exacerbado con la práctica de balance neto[2] que proporciona incentivos a la generación renovable ubicada en

2 La práctica del balance neto de energía está extendida en 46 de los estados en Estados Unidos (www.dsireusa.org) y en 7 países de la Unión Europea (Comisión Europea, 2015).

las instalaciones de los consumidores y basada en el esquema de medición y pago de la energía neta consumida a lo largo del período de facturación, por ejemplo mensual. Los consumidores con generación conectada en sus instalaciones que compensan su consumo con electricidad autogenerada o adoptando medidas de eficiencia energética reducen los pagos de aquellos costes regulados de redes y otros costes de política energética que se imputan mediante cargos volumétricos, es decir por kWh. Esto conduce a un efecto de subsidio cruzado por parte de los consumidores pasivos, que verán aumentados sus pagos por estos conceptos con respecto a aquellos consumidores activos que los podrán reducir de forma significativa. Al mismo tiempo, al ir disminuyendo la energía neta entregada por el sistema, requerirá que los cargos volumétricos incrementen progresivamente lo que aumentará el incentivo a instalar generación propia. En el límite, este efecto puede dar lugar a lo que se ha dado en llamar "espiral de la muerte del sistema" donde los consumidores acabarían incluso desconectándose de la misma red para generar su propia energía. Adicionalmente, como ya hemos comentado, el valor de la energía durante las horas del día va cambiando, por lo que compensar energía producida en unas horas del día con consumos durante otras horas crea ineficiencias y trasvase de rentas entre consumidores.

La conclusión es que esta práctica crea importantes distorsiones que deben ser evitadas en la medida en que los recursos distribuidos adoptados por los consumidores están creciendo de forma significativa. Los llamados medidores inteligentes, que permiten que la medida de la energía sea consumida o inyectada en la red en intervalos incluso inferiores a la hora, junto con un rediseño de las tarifas tal y como se explica más adelante, darían solución a este problema.

PRINCIPIOS BÁSICOS PARA EL DISEÑO DE PRECIOS Y CARGOS

Como se ha concluido en el apartado anterior los medidores inteligentes permiten establecer un sistema de precios con suficiente discriminación temporal para la energía neta consumida o inyectada en cada punto de conexión a la red en cada intervalo de tiempo establecido, horario o incluso inferior. De esta forma, el precio sería independiente de los equipos que el consumidor instalase detrás del medidor en sus instalaciones. Se ha venido discutiendo e incluso proponiendo sistemas de peajes de respaldo separados para la energía producida en las instalaciones del consumidor. El sistema de precios y cargos debe ser agnóstico respecto a las tecnologías o usos de la energía que el consumidor desee adoptar, es decir tecnológicamente neutro. Adicionalmente, los precios y cargos regulados deben ser simétricos respecto al consumo e inyección de energía (pagando al consumidor por la inyección de unidad de potencia en un instante y punto de conexión lo mismo que se cobraría por el consumo en ese mismo instante y punto de conexión, y viceversa) para cada intervalo de tiempo, cada hora o subperíodo, y en cada punto de conexión a la red. De esta forma no tendremos precios o cargos dependiendo del tipo de recursos distribuidos instalados por el consumidor, o de si se trata de un consumidor, un generador, o ambos.

Por otra parte, cuando se determine que ciertos costes, tales como por ejemplo incentivos a ciertas tecnologías o subsidios a consumidores vulnerables, se deben recuperar por medio de la tarifa, dichas ayudas o compensaciones deben explicitarse de forma clara y separada en la factura, y además ser cargados a los consumidores de la forma que se distorsione lo menos posible los precios y cargos regulados básicos asociados a la prestación de los servicios eléctricos propuestos en este artículo.

El sistema de precios y cargos asociados a la prestación y consumo de los distintos servicios eléctricos se compone de cuatro elementos aditivos principales: 1) el precio de la energía, 2) el precio o cargo de otros servicios relacionados con la energía, tales como las reservas operativas o la capacidad firme, 3) los cargos de los servicios de redes eléctricas de transporte y distribución, y 4) otros cargos para recuperar los costes de política energética u otras políticas gubernamentales que el correspondiente gobierno haya decidido recuperar a través de la tarifa eléctrica.

Los precios de la energía surgen del principio de eficiencia económica y deben reflejar el coste marginal o incremental de proveer el servicio o producto. Así la teoría marginalista para el cálculo de los precios *spot* o nodales de energía activa y reactiva en cada instante y en cada punto del sistema proporciona un sólido fundamento teórico, que trata de reflejarse en la vida real a través del establecimiento de mercados competitivos de energía y también de reservas operativas que determinan el precio de esos productos. Adicionalmente, sabemos que estos precios aplicados con discriminación local dependiendo del punto de conexión al sistema, resultan insuficientes para recuperar los costes de las actividades de red y por supuesto de los costes de las distintas políticas gubernamentales. Para el caso de los servicios de red, y siguiendo el mismo principio de eficiencia económica, veremos que se pueden diseñar cargos de red en los períodos de máxima utilización de la misma que reflejen el coste incremental de las inversiones futuras requeridas, quedando finalmente un coste residual de redes también a recuperar. En el caso de estos costes residuales de red o de los costes de las diferentes políticas gubernamentales, la regla a seguir para la recuperación de los mismos es que los cargos asociados deben diseñarse de forma que distorsionen lo menos posible las señales de precio obtenidas en el mercado y los cargos basados en los costes incrementales de redes y generación firme.

Como conclusión, la única forma de establecer una competencia en un mismo plano entre recursos distribuidos y centralizados para conseguir un sistema eficiente futuro, tanto en inversiones como en la forma en que se utilizan los recursos existentes, es acometer una profunda revisión de la estructura de precios y cargos regulados que los usuarios del sistema, sean generadores, consumidores, o ambos, reciben en cada instante de tiempo y dependiendo de su lugar de conexión en el sistema.

LA DISCRIMINACIÓN TEMPORAL EN EL PRECIO DE LA ENERGÍA

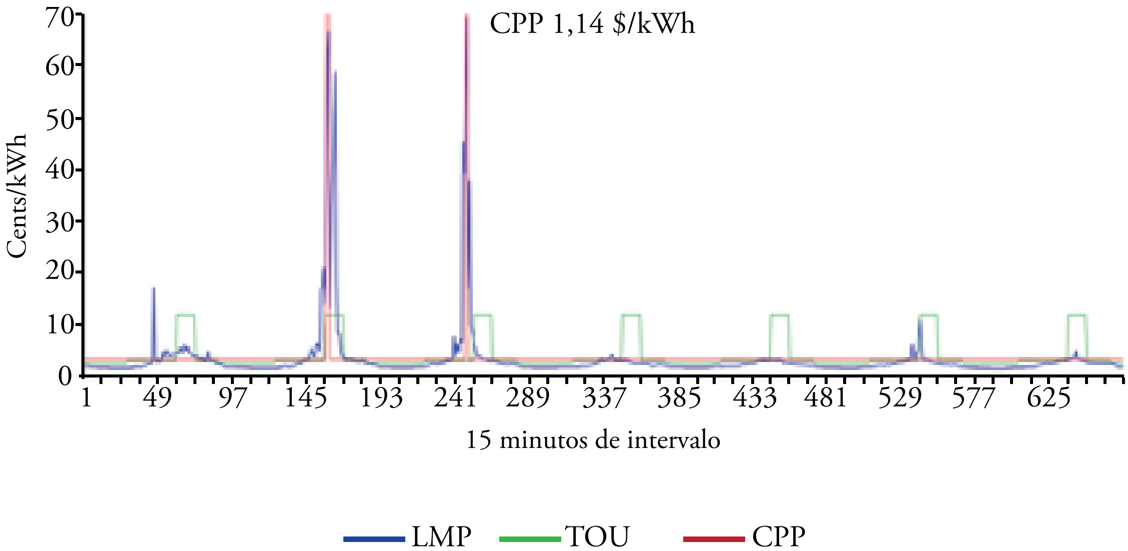
Actualmente los mercados mayoristas de electricidad reflejan la variación en el tiempo del valor de la energía tanto consumida como inyectada al sistema, el problema es que este valor no se traslada a los consumidores y a los recursos distribuidos con la misma discriminación temporal.

Por ejemplo, el gráfico 1 representa el valor de la energía en el mercado mayorista ERCOT en la ciudad de Austin (Texas). Pueden observarse en el mismo gráfico, las diferencias significativas entre este valor que debe tomarse como referencia (LMP) y las tarifas al consumidor final en diferentes alternativas, tanto en el caso

Gráfico 1

Precios mayoristas en ERCOT Austin (LMP), cargos por tiempo de uso (TOU) y cargos en períodos críticos (CPP)

(Semana en julio del 2015)



Fuente: Pérez-Arriaga *et al.* (2016).

de tarifas con dos valores según el tiempo de uso (TOU) o incluso con las tarifas bajo la modalidad de cargos muy elevados en los considerados períodos críticos (CPP).

La instalación de medidores inteligentes permitiría incluso a los consumidores residenciales obtener la señal de precio con suficiente discriminación temporal como para promover medidas eficientes de respuesta de su demanda al precio, tales como la instalación de termostatos, u otras relacionadas con una mejor gestión de sus medios de generación renovable con la instalación de baterías de almacenamiento de energía. Existen ya experiencias prácticas en este sentido donde los consumidores pueden acogerse al precio horario del mercado mayorista sabiendo que ello puede reportarles beneficios con una adecuada gestión de sus recursos. Este sería el caso de España con las tarifas basadas en el Precio Voluntario al Pequeño Consumidor (PVPC), que es la tarifa por defecto donde se trasladan los precios horarios del mercado mayorista a los consumidores domésticos acogidos a esta modalidad tarifaria.

CARGOS DE CAPACIDAD DE RED EN PERÍODOS DE MÁXIMA UTILIZACIÓN

Los costes regulados de las redes deben ser recuperados a través de señales económicas que en primer lugar promuevan eficiencia tanto en el corto como en el largo plazo, y en segundo lugar permitan recuperar el coste total reconocido de las mismas.

Como se ha comentado, los precios marginales de energía son las señales que crean eficiencia en el uso de los recursos existentes, es decir, en los aspectos operativos de corto plazo. Sin embargo, el excedente resultante de la aplicación de estos precios marginales en los distintos nudos del sistema (precios nodales) es insuficiente para recuperar los costes totales reconocidos de red.

La segunda señal para crear eficiencia en el largo plazo con respecto a minimizar la necesidad de inversiones futuras en red son los cargos de capacidad coincidentes en períodos de máxima utilización de la red. Estos cargos reflejan la responsabilidad de las inyecciones o consumos de potencia de los usuarios de la red en las futuras inversiones necesarias en la misma en aquellos períodos donde la red se encuentra más estresada. Al igual que los precios de la energía, estos cargos dependerán del nodo de conexión en la red y serán simétricos para las inyecciones y consumos de potencia (lo que se cobra por el consumo debe ser igual a lo que se paga por la inyección de la potencia en un mismo instante y punto de conexión). En ciertos períodos de estrés en la red el cargo puede gravar los consumos, fundamentalmente en las horas pico de demanda, mientras que en otros períodos el cargo puede gravar las inyecciones, en las horas pico de generación local en redes de distribución.

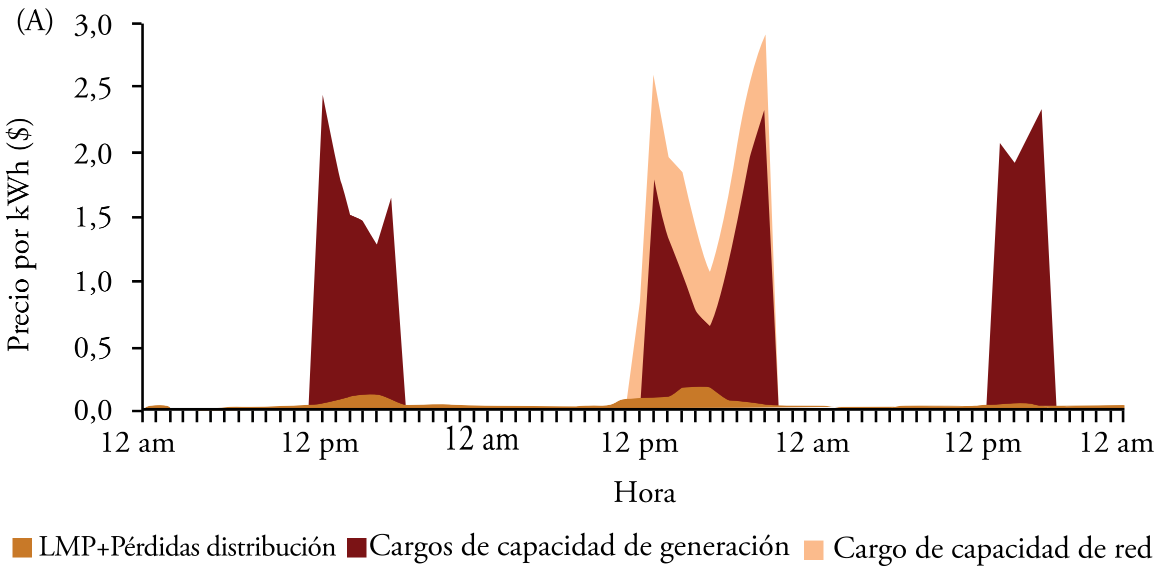
La misma lógica se puede utilizar para determinar los cargos de capacidad firme de generación coincidentes con períodos de máxima utilización de la capacidad de generación instalada, asociados a la existencia de mecanismos de remuneración de la capacidad en determinados mercados eléctricos.

En el gráfico 2 se muestra, para una determinada semana de julio en Chichester (Nueva York), el efecto de añadir a los precios de la energía sendos cargos de

Gráfico 2

Precio de la energía (LMP* + *Pérdidas en distribución*) y cargos de capacidad de generación y de red. Resultados para el condado de Westchester en Nueva York

(Ejemplo con bajo crecimiento de la demanda)



Nota: *LMP: precios nodales marginales.

Fuente: Pérez-Arriaga *et al.* (2016).

capacidad en determinados períodos, el primer cargo por coincidencia con los períodos de máxima utilización de la capacidad firme de generación, y el segundo cargo por coincidencia con el período de máxima utilización de la red.

Como se puede observar los cargos de capacidad de red o generación pueden ser importantes a lo largo de determinados períodos en el año y en determinadas horas. De nuevo los medidores inteligentes permiten reflejar estos precios adecuadamente con suficiente discriminación temporal y promover la respuesta eficiente de los consumidores mediante una adecuada gestión de sus recursos energéticos.

Sin embargo, las señales de eficiencia asociadas con la utilización de la red, precios mayoristas de energía, y cargos de capacidad de red, no son suficientes para recuperar los costes anuales reconocidos de red por lo que como se verá más adelante se deben añadir unos cargos complementarios para recuperar el coste residual de red junto con el resto de costes de políticas gubernamentales incluidos en la tarifa eléctrica.

LA COMPONENTE LOCAL DE LOS PRECIOS Y CARGOS

Los precios de la energía que reflejan el coste marginal de generar y transportar la misma, también cambian con la localización del consumo y la inyección de potencia en el sistema. La variación de precios de un lugar a otro refleja el coste marginal de las pérdidas que se producen en la red al transportar la energía, así como los sobrecostes operativos debidos a las restricciones, congestiones o problemas de tensión, que impone la red a los flujos de potencia.

Gráfico 3

Zonas de precios en el mercado integrado europeo de electricidad

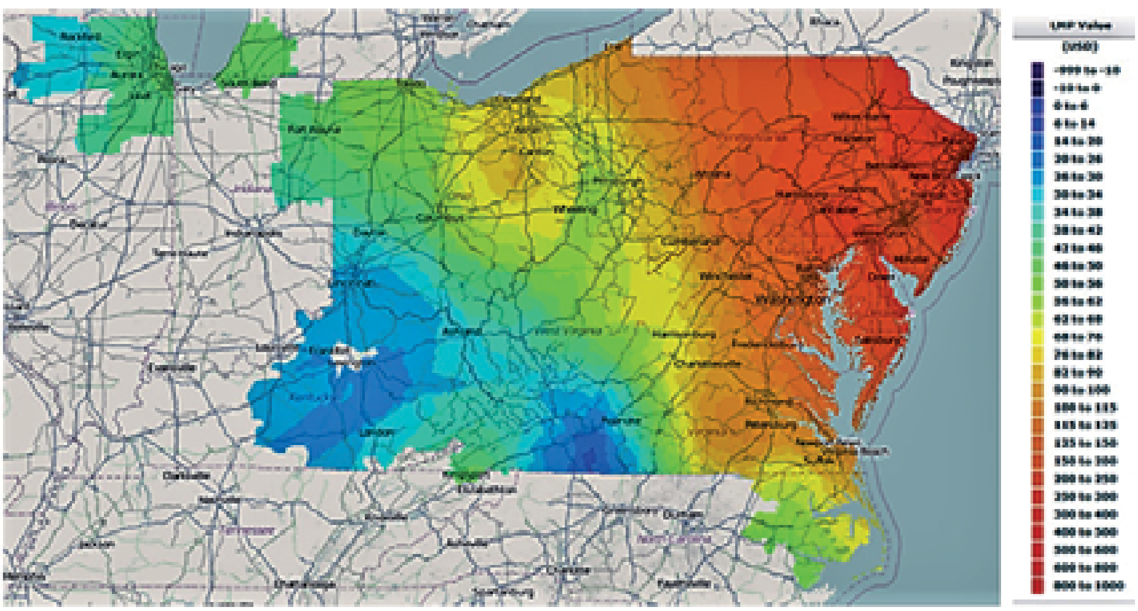
Fuente: Ofgem, 2014.

Este efecto de la variación local de los precios de energía eléctrica se recoge de distintas formas en los diferentes mercados. Por ejemplo, en Europa, el algoritmo que casa el mercado diario de electricidad considera diferentes zonas de oferta y demanda en cada uno de los países, y para cada zona obtiene un precio (gráfico 3). En el caso de ausencia de congestiones en la red los precios entre zonas coinciden, siendo diferentes en caso contrario.

Así mismo, en algunos mercados eléctricos en Estados Unidos, el operador del mercado calcula precios locales considerando un esquema muy detallado de la red de transporte que puede incluir miles de nodos o subestaciones. Por ejemplo, en el gráfico 4 se muestra la variación de precios nodales en la red operada por PJM con más de 11.000 nudos. Estos precios se calculan en el mercado horario y también en los mercados de tiempo real incluso para períodos inferiores a la hora (en PJM como muestra el gráfico cada 5 minutos).

Gráfico 4

Precios nodales en más de 11.000 nodos en PJM el 19 de julio del 2013 a las 4:05 pm.



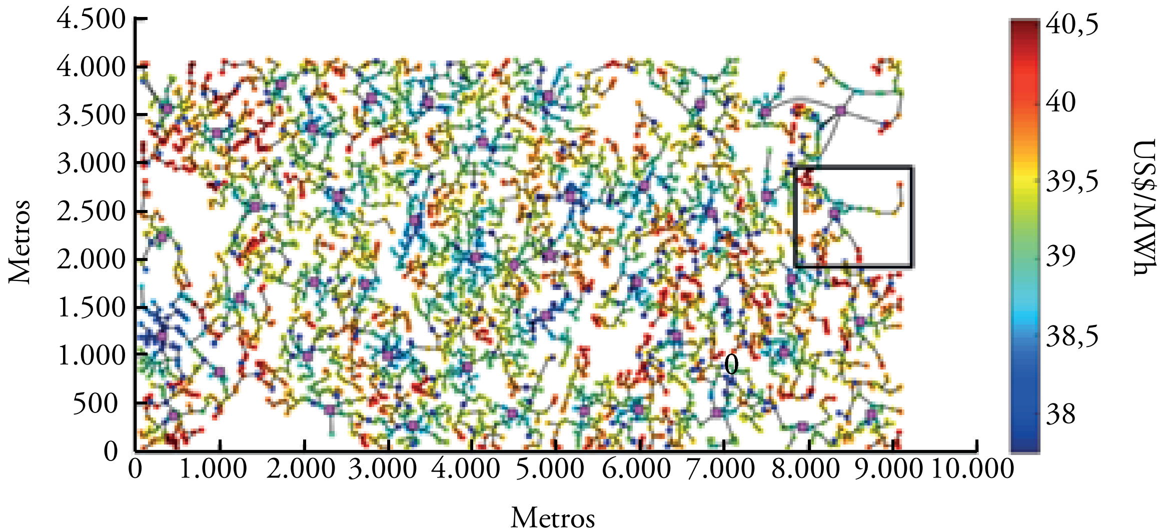
Fuente: Pérez-Arriaga *et al.*, 2016.

A pesar de estas diferencias de precios por zonas o incluso por subestaciones conectadas a la red de transporte de electricidad, calculadas en los mercados mayoristas, los precios que son cargados a los consumidores o recursos distribuidos conectados a las redes de distribución son iguales entre sí dentro de la misma zona o subestación de transporte. Es decir, hasta el momento, no existen experiencias reales donde el efecto local de las redes de distribución se tenga en cuenta cuando se calculan los precios de la energía para consumidores finales o recursos distribuidos.

En teoría sería posible con una representación detallada de las redes de distribución calcular también precios nodales de energía diferentes en los distintos puntos de conexión donde realmente se encuentran conectados los consumidores y recursos distribuidos asociados. Por ejemplo, en los gráficos 5 y 6 se muestra la distribución local de los precios nodales de energía en dos situaciones. En el primero, gráfico 5, las diferencias de pre-

Gráfico 5

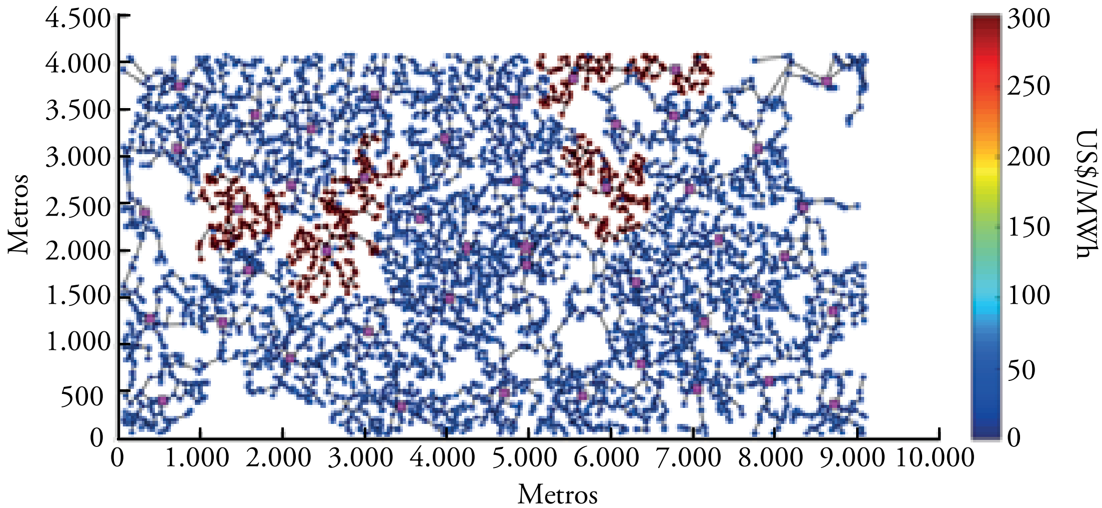
Diferenciación local de los precios marginales de potencia activa en redes de distribución durante una hora debido al efecto en pérdidas



Fuente: Pérez-Arriaga *et al.*, 2016.

Gráfico 6

Diferenciación local de los precios marginales de potencia activa en redes de distribución durante una hora debido al efecto en congestiones



Fuente: Pérez-Arriaga *et al.*, 2016.

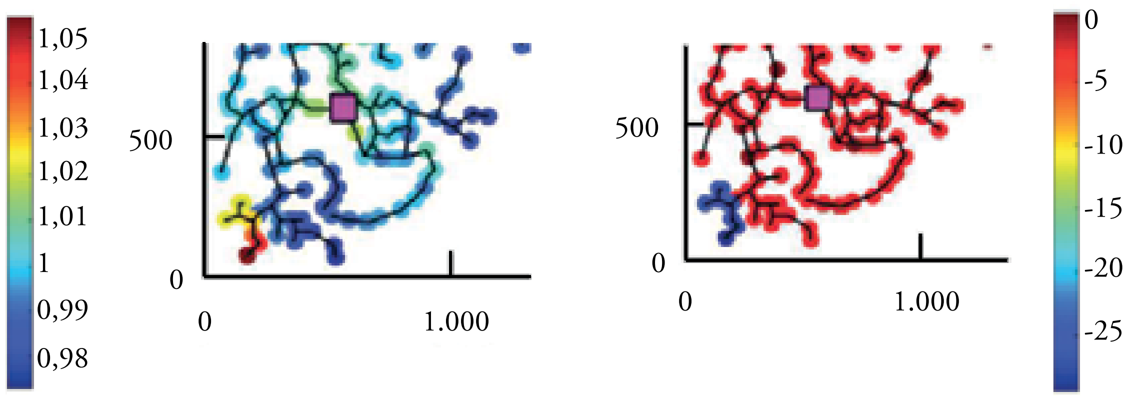
cios son menores entre los diferentes nodos y se deben únicamente al coste marginal de transportar los flujos de potencia que ocasionan pérdidas en la red, mientras que en el gráfico 6 aparecen diferencias de precios nodales mayores debido a que algunos tramos de la red presentan congestiones o problemas de tensión que llevan aparejados la necesidad de redespachar recursos distribuidos o desconectar demanda interrumpible a un elevado coste ($300/MWh).

En las redes de distribución, además de los precios de la energía por nodo, anteriormente comentados y referidos al consumo e inyección de potencia activa, se pueden calcular los precios nodales de potencia reactiva. Estos precios son indicadores y reflejan el coste ocasionado por los problemas de tensión que existen en la red, y que en redes de distribución suelen ser los más frecuentes. Por ejemplo, en el gráfico 7 se representan los valores de tensión observados en los diferentes nudos de la red y cómo se correlacionan con los precios nodales de potencia reactiva. Los precios negativos de potencia reactiva están asociados con problemas de tensión elevada e indican la necesidad de aumentar el consumo de potencia reactiva en dichos nudos. Estos precios pueden indicar a las compañías distribuidoras la existencia e importancia de los problemas y a partir de esta información tomar medidas para poder corregir dichos problemas. Por ejemplo, el operador de la red de distribución podría convocar una subasta competitiva con diferentes oferentes de recursos distribuidos que pudieran resolver los problemas detectados para después firmar contratos bajo los cuales poder gestionar dichos recursos cuando apareciesen los problemas comentados. Bajo estos contratos los recursos distribuidos seleccionados serían compensados económicamente. De esta forma, se podría aumentar la eficiencia del sistema en lugar de acudir a las tradicionales soluciones adoptadas por las compañías distribuidoras instalando nuevas líneas o subestaciones.

Por otra parte, además de los precios de la energía, los cargos de capacidad de red en coincidencia con los períodos de máxima utilización de la misma también

Gráfico 7

Valores de tensiones más altos en los nodos en pu (izquierda) y precios de potencia reactiva (derecha)



Fuente: Pérez-Arriaga *et al.*, 2016.

tienen una componente local relevante. Los períodos de máxima utilización de una subestación de alimentación a la red de distribución no tienen por qué ser los mismos que los períodos de máxima utilización de cada una de las líneas de media tensión que salen de dicha subestación, ni tampoco de cada uno de los transformadores de distribución de cada una de las líneas de media tensión que alimentan a los consumidores de baja tensión. Como se puede inferir el nivel de granularidad con el que finalmente se apliquen las señales de precio, en la práctica, es una decisión clave a tomar por el regulador.

Como conclusión, desde el punto de vista de promover la respuesta eficiente de los consumidores activos con recursos distribuidos es importante resaltar que las señales de precio con mayor granularidad serán las que produzcan mayor eficiencia, alineando los beneficios privados de los consumidores en su factura eléctrica con la reducción de costes totales en el sistema. Está claro que una mayor granularidad también implicará una mayor complejidad computacional, de información y comunicaciones, y de entendimiento y aceptabilidad por parte de los consumidores. Por tanto, existe un compromiso entre los beneficios incrementales en eficiencia y los costes añadidos en complejidad asociados a un mayor grado de granularidad en las señales de precios de energía y cargos de capacidad de red. Los reguladores deben determinar en la práctica en qué grado aplicar este nivel de granularidad en el diseño del mercado y en la asignación de los costes regulados a los diferentes usuarios del sistema de acuerdo a su localización.

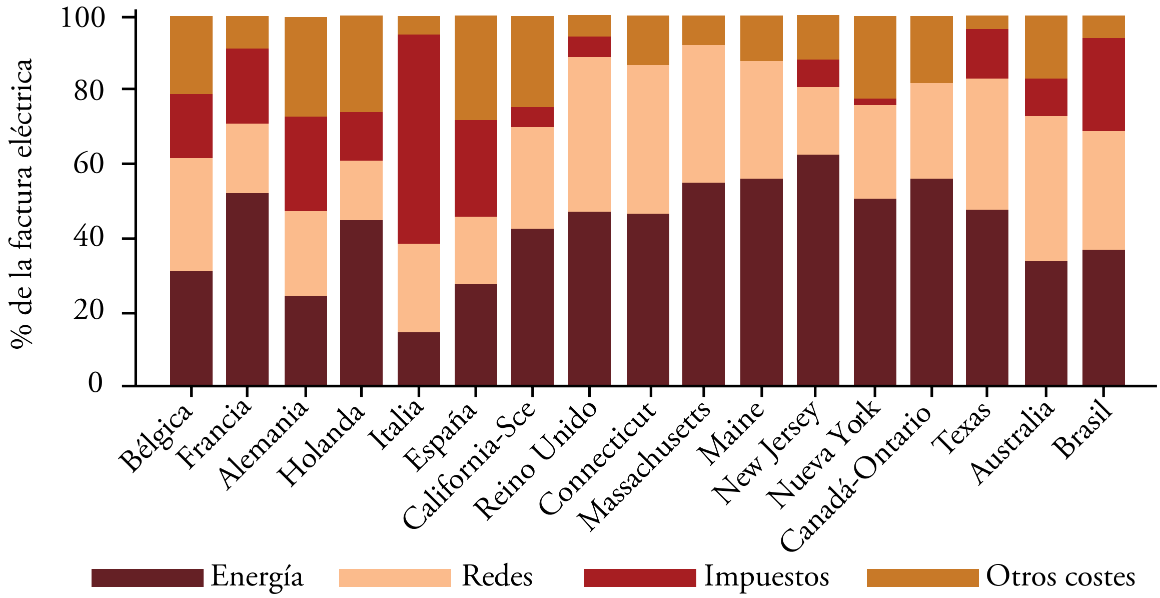
LOS CARGOS PARA RECUPERAR LOS COSTES RESIDUALES DE LAS REDES Y LOS COSTES DE POLÍTICA ENERGÉTICA Y OTRAS POLÍTICAS

La primera consideración que debemos tener en cuenta es que estos costes regulados incluidos en la tarifa eléctrica han ido cobrando mayor importancia en los últimos años. En determinados países estos costes junto con las tasas aplicadas al consumo eléctrico pueden superar el 50% del importe total de la factura, tal y como se observa en el gráfico 8.

La segunda consideración para el diseño de los cargos para recaudar los costes de políticas gubernamentales y los costes residuales de las redes no recuperados

Gráfico 8

Desagregación por categorías de costes de la factura eléctrica de consumidores residenciales en distintos países



Fuente: Pérez-Arriaga *et al.*, 2016.

mediante los cargos de capacidad de red, es que estos cargos deben distorsionar en la menor medida posible las señales de eficiencia de precios de energía y cargos de red que reciben los consumidores por sus consumos e inyecciones a la red con un suficiente nivel de granularidad tanto temporal como local.

Como se ha comentado, por lo general, en la actualidad ocurre lo contrario. En muchos países estos costes de redes o políticas gubernamentales se recuperan a través de cargos volumétricos por kWh que distorsionan la señal de precio de la energía. Lo anterior induce comportamientos ineficientes para el sistema por parte de los consumidores que instalan generación propia para compensar su consumo de energía y por tanto reducen su contribución al pago de este tipo de costes, sin que los mismos se vean reducidos por dicho comportamiento.

La alternativa para reducir estas distorsiones consistiría en diseñar estos cargos regulados como pagos anuales o mensuales por una cantidad fija por consumidor.

Una opción para determinar estos cargos fijos por consumidor es aplicar la teoría de precios de Ramsey que propone cargar a cada consumidor de forma inversamente proporcional a su elasticidad. El cálculo de dicha elasticidad es complicado por lo que en la práctica se podría utilizar un *proxy* dado por el impacto en la reducción de renta que tienen los consumidores debido al pago de la factura eléctrica. En el fondo, este *proxy* coincide con un indicador del nivel de riqueza. Por tanto, los costes de políticas gubernamentales y costes residuales de redes se podrían repartir entre los consumidores mediante un cargo fijo por consumidor calculado de forma proporcional, por ejemplo, a la tasa de bienes inmuebles o al tamaño de la propiedad con suministro eléctrico del consumidor, entre otras alternativas posibles.

COSTES A INCLUIR EN LA TARIFA ELÉCTRICA Y EL EFECTO DE DESCONEXIÓN DEL SUMINISTRO Y ABANDONO DEL SISTEMA

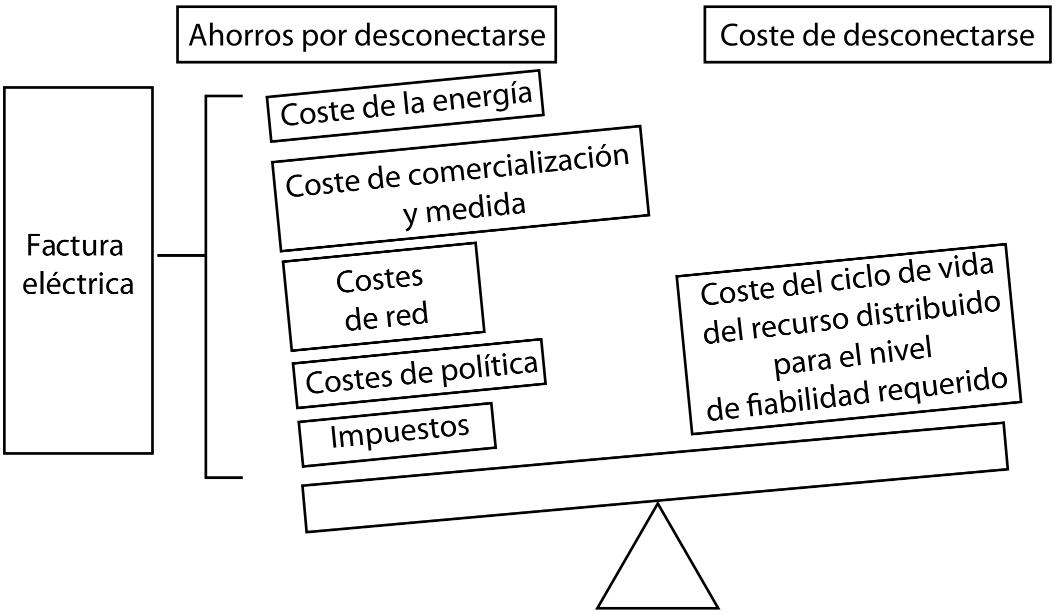
Con las reducciones de costes de los recursos distribuidos de generación y almacenamiento de energía experimentadas en los últimos años y las proyecciones para los próximos años donde se confirma esta tendencia, se observa en ciertos países, donde se dan las condiciones favorables y donde los costes de políticas gubernamentales son elevados, que cada vez un mayor número de consumidores está decidiendo desconectarse de la red, abandonar el sistema, y autoabastecerse con recursos energéticos propios, obteniendo de esta forma beneficios económicos.

En el fondo, el efecto observado de desconexión de la red es en último término una forma extrema de elasticidad de la demanda al precio que desde un punto de vista de la eficiencia global del sistema debe cuestionar los costes derivados de diferentes políticas gubernamentales que están siendo incluidos en la tarifa eléctrica.

El gráfico 9 compara el peso de los costes incluidos en la tarifa eléctrica frente al de los costes asociados a desconectarse de la red y autoabastecerse. Desde el punto de vista del consumidor, aparte de otras preferencias como las de ser autosuficiente o alimentarse únicamente con electricidad limpia, la decisión económica sería clara cuando el coste de la tarifa eléctrica, fundamentalmente debido a la importante

Gráfico 9

Costes y beneficios de la desconexión de la red desde el punto de vista del consumidor



Fuente: Pérez-Arriaga *et al.*, 2016.

carga de costes no directamente vinculados con el servicio eléctrico, supere los costes de autoabastecimiento que paulatinamente irán decreciendo.

Desde un punto de vista de eficiencia global, un diseño adecuado de la tarifa y de los costes incluidos en la misma debe evitar las prácticas ineficientes de desconexión de la red. El hecho de que los consumidores se desconecten de la red motivados por una excesiva tarifa, que incluye costes no relacionados con el servicio eléctrico y elevadas tasas, no reduce estos costes, y en último término, conduce a que los consumidores que siguen conectados aumenten su contribución a los mismos, produciendo progresivamente el efecto, anteriormente comentado, de un sistema financieramente insostenible ("espiral de la muerte del sistema").

Los gobiernos y el regulador energético deben sopesar sus decisiones con respecto a los costes no directamente vinculados al servicio que son incluidos en la tarifa y el efecto de la potencial desconexión de consumidores para autoabastecerse mediante recursos propios. En este sentido, se han propuesto algunas recomendaciones y existen distintas experiencias. Por ejemplo, en Batlle (2011) se discute la posibilidad de compartir el coste de los subsidios a las energías renovables entre los diferentes consumidores energéticos, en lugar de cargar sus extracostes únicamente sobre los consumidores eléctricos. Por otra parte, en Estados Unidos, una parte substancial de la financiación de la generación renovable se carga como tasas o impuestos en distintos ámbitos, local, estatal o federal, en lugar de incluirla en la factura eléctrica.

Finalmente, otra opción a explorar, aunque no exenta de potenciales trabas legales, para evitar la ineficiente desconexión de consumidores de la red, sería la de establecer un peaje de salida que deberían pagar aquellos que decidiesen abandonar el sistema. En este peaje de salida se incluiría la parte correspondiente a los costes residuales de redes y a aquellos costes de otras políticas incluidos en la tarifa eléctrica, que de otra forma otros consumidores acabarían pagando en su lugar. Existen cuestiones importantes relativas a la implantación en la práctica de este tipo de peajes de salida que deberían ser tenidas en cuenta por el regulador, tales como por cuánto tiempo y en qué cantidades este peaje debería calcularse. ¿Sería la compañía que ya no abastece al consumidor la encargada de recolectarlo? etcétera.

CONCUSIONES Y RECOMENDACIONES

El referido estudio *Utility of the Future* realiza una serie de recomendaciones prácticas dirigidas a reguladores y gobiernos en los aspectos que hemos abordado en este artículo. Estas recomendaciones son urgentes si queremos que el sistema eléctrico del futuro responda a señales de eficiencia donde, bajo las reglas de mercado, los recursos centralizados y distribuidos puedan colaborar y competir en igualdad de condiciones, y donde las reformas que se plantean promuevan una participación activa de los consumidores en invertir y gestionar los recursos energéticos del futuro. Como escribió Saint Exupéry, nuestro papel no es predecir el futuro sino facilitarlo.

A continuación, resumimos el decálogo de estas recomendaciones en lo relativo al establecimiento de un sistema eficiente de precios y cargos que valore la prestación y consumo de los diferentes servicios del sistema eléctrico.

- Crear un sistema de precios (para aquellos servicios que se proporcionan en mercados) y cargos regulados (para remunerar las actividades de red y otros costes de políticas gubernamentales incluidos en la tarifa eléctrica) como señales económicas directrices que reflejen en tiempo y lugar las condiciones específicas del sistema y que promuevan decisiones de operación y expansión eficientes tomadas por los agentes del mercado y consumidores con relación a los recursos centralizados y distribuidos que conforman el sistema eléctrico.

- Asegurar que los precios y cargos regulados son no discriminatorios y tecnológicamente neutros. Para ello, estos precios y cargos deben hacerse sobre la medida de energía o potencia en el punto de conexión al sistema, es decir sobre el consumo e inyección de energía o potencia en cada intervalo de medida en dicho punto de conexión, en lugar de sobre los diferentes equipos que conforman la instalación del consumidor. En otras palabras, no se puede ir más allá del contador entrando en los equipos del consumidor. Además, los precios y cargos deben ser simétricos, pagando por la inyección de unidad de potencia en un instante y punto de conexión lo mismo que se cobraría por el consumo en ese mismo instante y punto de conexión, o viceversa.

- Promover el desarrollo de una moderna infraestructura de contadores inteligentes y comunicaciones asociadas en los puntos de conexión al sistema, donde se conectan generadores, consumidores, y los que realizan ambas actividades. Se trata de un requisito imprescindible para poder aplicar el sistema de precios y cargos propuesto con el suficiente nivel de granularidad temporal y local.

- Establecer el nivel de granularidad adecuado en las señales de precios y de cargos de acuerdo con las características de la infraestructura de medición, del sistema eléctrico y del contexto regulatorio. Para ello se deben valorar las ganancias en eficiencia asociadas al aumento progresivo de dicha granularidad con relación a los costes de implantación, complejidad y aceptabilidad por parte de los consumidores, y otros aspectos de equidad en el diseño de las tarifas.

- Diseñar los cargos para recolectar los costes residuales de las redes junto con los costes derivados de políticas gubernamentales y tasas incluidos en la tarifa eléctrica de tal forma que distorsionen en la menor medida posible las señales eficientes de precios de la energía y cargos de capacidad de red o de potencia firme que reflejan la variación de los costes del sistema. En particular evitar cargos volumétricos por kWh para recuperar estos costes residuales y migrar hacia cargos fijos por consumidor, que en el caso de los consumidores residenciales pueden hacerse proporcionales, por ejemplo, a la tasa de bienes inmuebles o al tamaño de la vivienda o propiedad del consumidor.

- Asegurar que los precios de energía reflejan una suficiente diferenciación en el tiempo. Transmitir a los consumidores con medidores inteligentes la variación horaria de precios observada en los mercados mayoristas de electricidad con factores de pérdidas marginales para cada uno de los niveles de tensión en la red puede ser un buen punto de partida.

- Implantar cargos de capacidad de red coincidentes con los períodos de máxima utilización de las infraestructuras. Estos cargos deben reflejar las contribuciones de los usuarios de la red a los costes incrementales de las infraestructuras de red en los períodos de máxima utilización de las mismas, coincidentes con períodos de máximo consumo o períodos de máxima generación locales. En los mercados con mecanismos de remuneración de la capacidad, también pueden establecerse cargos de capacidad en los períodos de escasez de la potencia firme generada. Todo ello atraerá inversiones desde el lado de la respuesta de la demanda y de otros recursos distribuidos que resultarán eficientes para el sistema en su conjunto.

- Aumentar progresivamente la discriminación local de las señales de precio y cargos de red en las redes de transporte y de distribución de electricidad. Las ganancias de eficiencia serán mayores en aquellas zonas del sistema donde habitualmente se presenten congestiones o problemas de tensión. Por el contrario, la discriminación local presenta una mayor complejidad en el cálculo de precios y cargos, y en el caso de los cargos de red resulta contraria a la práctica habitual de socialización de los costes de las redes, levantando en último término la discusión sobre equidad en las tarifas.

- Explorar la utilización de las señales de precio de potencia reactiva en las redes de distribución para detectar problemas de tensiones que son los más frecuentes en esas redes, y permitir al operador de la red de distribución identificar recursos distribuidos que puedan ayudar en la resolución de dichos problemas, reduciendo de esta forma la necesidad de nuevas inversiones en redes.

- Explorar métodos para resolver los potenciales problemas de equidad asociados a la implantación de señales locales de precios y cargos de red. Los consumidores residenciales y también los consumidores vulnerables deben disponer de mecanismos que les den seguridad financiera sobre la incertidumbre creada por la volatilidad de precios y cargos asociada a las señales económicas propuestas. En este sentido, los reguladores deben promover mecanismos de cobertura para compensar variaciones mes a mes en la factura o igualar tarifas medias por zonas pero manteniendo el incentivo para aquellos que reaccionen en la dirección correcta de reducción de costes del sistema.

Además de los temas relacionados en este artículo relativos al establecimiento de un sistema eficiente de precios y cargos, el estudio de MIT y Comillas también propone recomendaciones en otros campos relativos a la mejora de la regulación de las compañías distribuidoras de electricidad, el establecimiento de una estructura verticalmente desintegrada y funcional de la industria eléctrica, la mejora de las reglas de funcionamiento de los mercados mayoristas de electricidad, y finalmente otras recomendaciones sobre el valor local de los recursos distribuidos y economías de escala a tener en cuenta cuando se diseñan políticas de promoción de tecnologías que puedan ser desplegadas en modo centralizado o distribuido.

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New regulatory and business model approaches to achieving universal electricity access*

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Abstract

Universal access to electricity should be achievable by 2030, the deadline proposed by the UN in its Access for all initiative. However, progress so far has been too slow. The International Energy Agency estimates that by 2030 still more than half billion people, mostly in Sub-Saharan Africa and South Asia, will lack electricity access. Technology and sufficient funding exist, yet other key components of the solution are clearly missing. This paper argues that an essential lacking component is a regulatory and associated business model package that is well adapted to the specific characteristics of electrification in the least developed countries, and that can be supported by sound quantitative analysis of the costs and benefits of every considered option.

Keywords: Electricity access, off-grid, rural electrification, power sector regulation.

INTRODUCTION

A large number of people lack electricity access or have access of very poor quality. Progress in improving the situation is slow and estimates for the future –like the recent ones issued by the International Energy Agency (IEA, 2016)– are pessimistic about achieving universal access by 2030, and even in 2040.[2]

Despite the grim outlook, there are multiple positive signals. The level of global awareness has grown substantially over the last decade, as indicated by a slew of

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2 The International Energy Agency estimates that by 2040 still half billion people (down from 1.2 billion today), mostly in Sub-Saharan Africa and also in South Asia, will lack electricity access. In addition, an undetermined and probably larger number of people have very poor quality electricity service, which hardly can be considered as "access".

new electrification initiatives announced by many of the concerned governments and the increasing level of available international funding.[3] Substantial –albeit insufficient– progress has been made in most countries. New regulatory approaches and business models have been proposed and some have also been tested, see for instance (Bhattacharyya, 2013; Tenenbaum *et al.*, 2014; Palit and Bandyopadhyay, 2015; Africa GreenCo, 2010; Maithani and Gupta, 2015; Barnes, 2007; Wimmer, 2012). There are numerous studies and experiences upon which one can draw and the social sciences have made important contributions in understanding the many dimensions of the problem. The technology to provide universal access is available and the investment necessary to do it –the IEA estimates a total amount of $48 billion per year until 2030– is certainly significant, but it can be raised.[4] It is therefore clear that the answer to the lack of progress has to be found elsewhere.

This paper argues that sound regulation and an ensemble of compliant, contest-relevant business models are essential missing components to achieving universal access to electricity in the least developed countries. Such regulation and the business models that fit within it must be well adapted to the specific characteristics of electrification in each country and must be informed by rigorous quantitative analysis of the costs and benefits of every option, as well as the concomitant social, political, cultural and administrative factors. Since sound regulations and business models can only succeed fully if they happen in a stable country context (where legal security is guaranteed by independent institutions and a good track record of governance) the task at hand acquires even greater proportions in the context of politically unstable countries.

The key role of regulation for electrification

Essential features of the power sector that are taken for granted in the regulation of electricity in industrialized countries simply do not hold in the least developed ones. As a consequence, many customary regulatory approaches in more developed countries have to be reinvented in the context of electrification access.

3 See http://www.se4all.org for instance.

4 These $48 billion per year are less than 2% of the annual cost of electricity in OECD countries.

Two indispensable elements are thoughtful, context-specific regulatory guidelines that enable viable business models in each country, and credible institutions that have the autonomy to implement and enforce this regulation. Without these, firms will not even consider investing in electrification in a given country,[5] given the estimated magnitude of the required outlays. For instance, according to the International Energy Agency, only Sub-Saharan Africa will require more than $300 billion of investment to achieve universal electricity access by 2030. Reasonably sound regulations and institutions are required to give private investors confidence that the financial risk is manageable.

Regulation must clearly assign the responsibility to provide reliable, efficient and affordable electricity, establish the procedures to identify and resolve conflicts, and mitigate avoidable risks that may arise from the coexistence of different types of suppliers. In general, regulation must establish the supply tariffs and any necessary compensation mechanisms –either directly allocated or via cross-subsidies between consumer categories– to achieve economic viability of the supplying companies. Regulation must also make compatible centralized and distributed approaches, as well as the joint presence of the incumbent companies, large corporations, and small developers.

Viable business models

The objective of an ambitious electrification program that is commensurate with the needs of the least developing countries is to develop an implementable and scalable business model for universal energy access that can attract large-scale private investment, both from a multiplicity of entrepreneurs and from

5 Practically all countries in the world have an institution in charge of regulating network energy services, *i.e.* electricity and natural gas. Such institutions belong in the area of public administration –many of them are in fact departments of a ministry–, and in most industrialized countries they are set up as authorities or commissions endowed with diverse levels of independence with respect to the government. The rationale for such arrangements is to protect the technical activity of the regulator from being subject to political instability or excessive interference with electoral concerns or with pressures by lobbyists. Such institutions are known under the term "energy regulators". There are more than 200 in the world, organized in 12 regional associations that are members of the International Confederation of Energy Regulators.

the leading large energy companies that so far have had very limited exposure to electrification activities in these emerging markets. The focus must be on both off-grid and on-grid markets across generation, distribution, transmission and customers –both households and businesses– in those least developed countries that have a minimum set of institutional and regulatory conditions as to be able to attract serious investment funds.

Most of the existing off-grid solutions, whilst having a very positive impact in delivering basic energy services, are not focused on productive uses – the main driver of job creation and economic growth. It is therefore necessary to upscale the ambition of off-grid electrification efforts. This could be helped by the ongoing trend of cost reduction and performance improvement of the technologies for electricity supply and demand, which now allow for addressing electrification in different ways. In addition, innovative financing schemes could combine the diverse payment capabilities of residential consumers with specific electricity tariffs for the commercial and industrial customers, so that new electrification becomes as economically viable as possible.

Electrification efforts must be aware and take advantage of technology improvements, both from the demand side –efficient appliances, and demand management and communication technologies– as well as from the supply side –on grid/off-grid generation technologies, storage, and grid control devices, both for utilization in microgrids or in grid extension–. The new technical capabilities and reduced costs of off-grid supply technologies make possible business models that could not have been imagined some years ago. Leapfrogging opportunities might avoid or minimize the use or extension of unnecessary legacy investments.

After this introduction, section 2 presents the assumptions underlying the regulatory compact that is prevalent in more developed countries. A different set of assumptions is needed in least developed countries, as shown in section 3. The open issues that the new assumptions raise are discussed in section 4. Finally, section 5 closes with the broad guidelines that must inspire the regulation and business models that could enable universal electricity access by 2030.

ASSUMPTIONS IN THE TRADITIONAL REGULATORY COMPACT FOR ELECTRICITY SUPPLY IN MORE DEVELOPED COUNTRIES

There is a well-established theory and practice of power sector regulation in the developed world –with different versions ranging from a traditional cost of service framework with vertically integrated utilities to liberalized wholesale and retail markets with full unbundling of activities– that has served many countries well for several decades (Pérez-Arriaga, 2013; PURC, 2017).

This regulatory compendium is presently being challenged from several overlapping directions, including the drive towards a decarbonized power sector, the increasingly strong presence of distributed energy resources, the operation of power systems with large amounts of intermittent renewables, and the growing interest in cross-border trade in regional markets of increasing geographical scope.

These trends require adaptations of the regulations of the different activities and the rules of the wholesale and retail markets. However, the fundamentals of the regulatory approach remain stable in more developed countries, despite the need for improvements. The main reason for this is the permanence of some core assumptions about the supply of electricity that are taken for granted, but strongly influence the regulatory framework. The focus of this discussion will be on the activity of distribution, which is closest to the provision of electricity access, although the bulk power system is affected by grid extension electrification and will be also considered. What are these assumptions?

- *Supply to consumers is provided by grid connection.* All consumers are supplied by connection to the main grid, which is typically part of a large national or even regional interconnected system. This grid provides high reliability and a very stable frequency of the supplied AC power. New technologies are not disruptive enough to change this paradigm.

- *The utility is the accepted business model.* The perpetual supply of electricity is guaranteed by a "regulated monopoly with a territorial franchise" or "utility model", *i.e.* a network company with a business model based on guaranteed economic viability.

- *The regulator is in charge of those consumers connected to the grid, which, in practice, are all the consumers.* Except for the very special cases of a few places with highly remote access that have their own autonomous electrical supply, everybody is connected to the grid. Therefore, power sector regulation is implicitly designed for grid-connected consumers. The issue of how to deal with consumers that disconnect from the grid has only recently become relevant, as grid defection has started to be considered a possibility.

- *Sufficiency of upstream supply.* Connecting new consumers does not imply major changes at a bulk power system level, since demand growth happens gradually, in small increments and with the benefit of a fully developed network and generation infrastructure.

- *Electricity is an indispensable component of everybody's life.* Electricity access has become indispensable for customary household, community and productive activities. For decades, reliable and adequate electricity supply has been a fundamental component of our infrastructure and a core tenant of the functioning of our society.

- *Almost perfect continuity of supply.* The distribution network basically always maintains the connection between the transmission substations and the final customers connected to the distribution network. The continuous upstream supply of electricity is taken for granted and permanent continuity of supply is basically guaranteed. In this context, discussion about reliability or quality of supply refers to the efforts to reduce even more the few hours or minutes per year when the supply is interrupted or to decrease distortions in the almost perfect waveform of the voltage that is supplied.

- *The grid provides AC power and a full range of AC appliances is available for purchase.* All kinds of appliances are available at the standard voltage (220 V or 110 V, depending on the country) even though many of them actually function in DC (computers, TV, phones, LED lights, and all kinds of electronic devices).

- *The level of demand that the distributor is committed to supply has no external limits and aggregated demand can be accurately estimated.* The infrastructure of electricity supply is designed so that it does not limit or constrain the demand that the end customer may require, except for the self-imposed limits that the customer may voluntarily accept when contracting the supply (in some countries). The reliability level on the point of supply does not have an impact on the level of demand, since this reliability level is basically the same everywhere and close to 100%. Typically the future demand is estimated with a small error margin.

- *Regulated tariffs cover the cost of supply, and the distribution network costs in particular.* Customers are charged for the cost of the distribution service and this is included in their final tariffs, which are established by the regulatory authority.

- *Theft and non-payments are under control.* Failure to collect the tariffs and theft are generally minor problems in developed countries. If cases occur, they are promptly investigated and can be considered to be under control.

- *Energy poverty affects a minority of consumers.* Most customers can pay for the cost of electricity and it is a not a substantial component of their household budget. Nevertheless, in most industrialized countries, a significant part of the population –about 10% in the EU, for instance– are "energy poor", meaning that they live in households that pay for the cost of energy supply using more than 10% of their budget.

- *Cross-subsidization is implicit and socially is a non-issue, except sometimes for social tariffs.* In addition to social tariffs (whose extra costs are typically charged as an uplift on all the other tariffs), in industrialized countries there is a great deal of cross-subsidization of distribution costs, between those consumers living in densely populated urban areas, and the consumers living in the countryside, where the density of demand is much lower. Cross-subsidization is considered to be normal and most people are not even aware of its existence.

The next section will examine the status of these assumptions in the power sectors of least developing countries where a high percentage of the population lives without electricity access.

WHAT IS DIFFERENT IN COUNTRIES WITH A SUBSTANTIAL LACK OF ACCESS?

Electrification in least developing countries –and more specifically in rural areas, where the majority of people lacking access live– has to start with a different set of assumptions, which should determine condition the regulatory approach. Therefore, the customary regulatory approaches adopted in more developed countries and assumed to be universally valid, in particular regarding distribution and the design of tariffs, have to be questioned when dealing with electrification in developing countries. The assumptions in the last section will be examined now one by one.

Supply to consumers is provided by grid connection

It is important to realize that lack of access to electricity happens in very diverse situations. Many people without access are located in remote areas that will not be reached by expansion of the grid for a long time, maybe never, thus, other viable off-grid solutions have to be implemented. On the other hand, many people live close to the existing power grid ("under the grid", as opposed to "far from the grid"), but they lack an electricity connection, because the connection and/or monthly fee are too expensive or because the incumbent distribution utility is disinterested in providing the connection.[6] Off-grid technologies could provide an alternative or at least a temporal bridge to a future grid connection for these customers. Therefore, off-grid systems can be a solution not only for extremely remote locations that will never see the centralized grid, but also for communities that will not receive reliable centralized electricity for many years, and they could create a basic level of infrastructure that could potentially facilitate the integration with the main grid, if later deemed to be the best option.[7]

6 When we mention areas where electricity grids exist, we must specify that we refer to medium (e.g. 11 kV) and low-voltage (220 or 110 V, depending on the country) distribution grids, because people living near a high-voltage line built for long-distance transmission of electricity cannot technically connect to it, so they are in the same position of people living far from any network.

7 An interesting topic to be explored is a better understanding of why there is widespread perception that off-grid electricity is not "real" electricity and what may shift people's beliefs toward accepting it as a real, alternative form of power.

Therefore, although reliability, stable frequency, and lower cost of centralized generation because of economies of scale have made grid connection the indisputable best option for electricity supply worldwide meeting the increase in demand and universal access to energy will, in general, require a combination of grid extension and off-grid solutions in the short (and maybe even longer) term. The strong on-going cost declines in solar photovoltaic and storage technologies, combined with innovative business-models, can further enhance the viability of off-grid options.

The utility is the accepted business model

In most least-developed countries the incumbent distribution utilities have failed to provide universal access. The causes are diverse. Frequently the distribution company is in dire financial straits and therefore unable to invest in electrification. The origin of this situation might be heavily subsidized tariffs that are unable to pay for the supply costs of both the extension of the grid and the purchase of the bulk power to be distributed. Most of these distribution companies are publicly owned and the corresponding national or provincial governments often cannot cover the deficit, thus augmenting the financial difficulties of these companies. Trying to connect more customers would, thus, only increase their losses.

However, the bottom line is the "viability gap", *i.e.*, the difference between the actual cost of providing the service and the revenues from the regulated tariffs or what the consumers can pay (this concept will be explained in more detail later). Distribution of electricity is expensive in rural zones with low, dispersed demand, which is a common situation in least developed countries. The cost per connection typically can be several times more expensive than it is in densely populated urban zones. Since many of the people living in these rural areas are poor, they cannot cover these high supply costs and need some kind of subsidy, which the government may not be able (or willing) to provide. In developed countries that have reached complete electricity access, the most frequently adopted practice is to apply a uniform tariff to all low voltage residential consumers in the country –or to all being supplied by the same distribution company– regardless of whether they are located in an urban, semi-urban or rural area. Unfortunately, this simple cross-subsidization approach cannot be used in least developed countries, where the average level of income is much lower, and the percentage of rural households without access is large.

Therefore, the regulator is trapped in an unsolvable dilemma: (i) either charge higher tariffs to rural consumers, which most could not pay and which violates the commonly established rule of uniform tariffs regardless of the location on the grid, or (ii) charge the existing lower tariff that applies to on-grid consumers also in rural areas, knowing that this would deteriorate the financial situation of the distribution companies.[8]

In reaction to this situation, entrepreneurs have started to occupy the empty space left by the incumbent distributors in many countries (Tenenbaum *et al.*, 2014; Palit and Bandyopadhyay, 2015). These developers offer a diversity of off-grid solutions to people without electricity access or with access of such poor quality that they need an alternative electricity supply. This shatters the traditional paradigm of the traditional utility, as a regulated monopoly with a territorial franchise.[9] Depending on the country, these entrepreneurs could be unregulated and only subject to some basic industrial safety rules and organized as cooperatives, franchisees of the incumbent distributor, or new utilities specialized in off-grid supply (Bhattacharyya, 2013; Tenenbaum *et al.*, 2014; Palit and Bandyopadhyay, 2015; Wimmer, 2012 and Box 1).

In the last few years, a new alternative approach has emerged; that deviates even more from the traditional utility-based paradigm; solar kits. These kits weigh about 4 Kg, with a modest solar panel of about 15 W and a lithium-ion battery of 20 Ah at 12V with a charge controller. They can supply four 2.5 W LED lights (one a portable solar lantern) and a phone charger for the typical needs of one day. These solar kits are easy to install, fully plug-and-play, have several USB ports, and are grid compatible in case the grid eventually arrives. Their unique combination of functionalities means they are *categorized as appliances*,

8 This is further complicated by the widespread issue of an "entitlement mind" or "attitude" held by many in the poorer communities (especially in agriculture) that they should not have to pay. See Maithani and Gupta, 2015: 122.

9 A similar phenomenon –known as "grid defection"– has started to take place also in more developed countries, at individual or even communal level, see (MIT, 2016).

since they can be sold by a commercial outlet without the involvement of an off-grid developer company or a utility. The users can bring the kit to the shop for repairs or enhancements with additional modules. This is a technology change that results in a radical transformation of the associated business model. Home solar kits are experiencing a notable rate of penetration (Bloomberg, 2016) but are largely unaffordable for the bottom of the non-electrified pyramid and some kind of subsidy, or a well-adapted financial approach,[10] are needed so that most households can afford these solar kits, see (Bensch *et al.*, 2016; Grimm *et al.*, 2016).

Off-grid technologies for households (beyond solar lanterns) can be economically viable: i) for the wealthier fraction of the non-electrified population, ii) when some donor institution or some governmental subsidy can make up the difference between the consumers' willingness to pay and the actual supply cost, or iii) when the service is so basic and is provided with such rudimentary means (*e.g.* no meters, non-standard poles –just using trees, rooftops and bamboo canes–, no charge controllers) that the poorest people can afford the most basic –one light and one phone charge– and unreliable service. Also, perhaps (depending on the affordability level), when a clever payment scheme is designed to accommodate the liquidity constraints of the beneficiaries, see M-KOPA, for instance.[11]

The regulator is in charge of those consumers connected to the grid, which in practice are all the consumers

Regulation in least developed countries has been frequently written thinking only of consumers that are connected to the national grid, to a large regional grid or to the power system supplying an island. Access to energy amongst the population living in areas not served by existing networks has been frequently ignored in the regulators' mandate. Yet regulators can help accelerate access to electricity by establishing sound regulation supportive of viable business models, and they should be always included among the actors of the worldwide struggle to reach universal access to energy. Coinciding with the growing global awareness

10 Approaches that account for the low cash flows of the poor –for instance pay-as-you-go or pay-to-own systems, sometimes integrated with the mobile banking sector– have been implemented in Kenya, Tanzania and Uganda. See M-KOPA, for instance (http://www.m-kopa.com/products/).

11 Ibid.

about widespread lack of electricity access, during the last decade most countries have enacted pieces of legislation finally addressing the electrification problem. As a consequence, few countries have long-standing experience implementing regulations that address electricity access and, in particular, off-grid electricity supply and the coexistence of on- and off-grid technologies (Tenenbaum *et al.*, 2014; UPERC, 2016).

Sufficiency of upstream supply

Shortage of available generation to meet demand is a rare occurrence in more developed countries, as they typically have a sufficient margin of generation capacity and energy, and demand typically grows slowly and predictably. This is not the case in low energy access countries, where grid-connected consumers' demand typically grows briskly, and the demand growth of those not connected depends on the ambition and implementation success of the electrification plan, if there is one. When more than 50% of people in a country live without electricity access (as is the case in many sub-Saharan countries and in some states in India) an electrification plan that aims for universal access necessarily has to account for sizeable investments in generation and a thorough redesign of the transmission and sub-transmission (also called high-voltage distribution) grids (MININFRA, 2016).

Electricity is an indispensable component of everybody's life

In more developed countries, electricity access, in any amount that might be needed, is taken for granted. On the contrary, moving from a life without electrical supply to using some basic electric home appliances and electricity-powered productive devices leads to significant changes in the wellbeing of individuals and communities across several dimensions: comfort, education, health, leisure, entertainment, and economic productivity. A quantitative estimate of the magnitude of the global social return on the investment in electricity supply is necessary to establish priorities of governments, international aid organizations and financial institutions when deciding how and when to allocate financial resources among different recipients and objectives. This is an open research area, so estimates vary widely (Burlig and Preonas, 2016; Lenz *et al.*, 2015; Bhattacharyya, 2013). It is well known that electricity is an essential enabling factor of human development, but by far not the only one, therefore outcomes are highly dependent on conditions.[12]

Almost perfect continuity of supply

The situation of continuity of supply is very different in least developed countries.[13] At the most basic level, the matter of concern is whether some levels of quality of supply are worth paying for, and if other alternative sources of electricity supply should be considered instead, including returning to the traditional candles and kerosene lamps. A very important practical topic for regulators and electrification planners is the relationship between the expected or actual reliability levels, the actual or expected consumer demand, and their willingness to pay for some quantity of demand at some level of quality of supply, as the three factors are closely interrelated.

The most immediate concern is how to communicate the concept of "reliability" in a context with a diversity of supply technologies and business models, a substantial number of people without access, and many others with significant curtailments that vary in frequency, duration, and intensity. A precise definition of reliability is needed by regulators to set targets, incentives, and penalties to the distribution companies; by developers to negotiate with potential customers and communities; and by consumers to understand the product that they are purchasing and the relationship between how much they pay and the reliability level that they get.

12 See the paper "The economic lives of the poor", http://economics.mit.edu/files/530, to understand the trade-offs and choices made by people in the lowest income brackets between food vs. education vs. water vs. energy vs. entertainment.

13 A recent survey revealed the dismal state of electricity supply in rural India. In the six study states: Bihar, Jharkhand, Madhya Pradesh, Uttar Pradesh, West Bengal, and Odisha, the average electrified household reported receiving only 12.5 hours of electricity per day; in Bihar and Jharkhand, only 9 hours were available. Households also reported 3.6 days of blackouts (no supply for continuous 24 hours) per month. On a 0-2 scale, electrified households reported an average satisfaction with their electricity access of only 0.95. See more at http://www.ideasforindia.in/Article.aspx?article_id=1757#sthash.yMRULgOK.dpuf

The use of a single metric for reliability is complicated because reliability is multidimensional (curtailments vary in frequency, duration and intensity) and because of the different nature of the supply in each case.[14] Individual off-grid solutions that are only based on solar PV and batteries typically provide reliable power for a limited and somewhat variable number of hours per day, every day. Since the limiting factor is the amount of energy that can be consumed daily, energy intensive appliances are mostly out of question. The reliability can be improved by being connected to a microgrid (although it may depend on the adopted demand management scheme, as each consumer now shares a scarce resource with others) and by adding a non-intermittent generation source, such as a diesel or biomass generator. Micro-grids and stand-alone systems with storage can be designed and managed so that at least essential loads are supplied with reasonably good continuity of service. In contrast, grid-connection offers a basically unlimited power capacity, allowing the use of all kinds of appliances, but it is the experience in many developing countries that grid power is unreliable, with quality of supply being worse in remote rural areas, so that in many cases electricity supply systematically fails at those periods of time when it is most needed, with uncertain patterns. Another typical difference in a developing setting is the lack of a strong infrastructure for grievance redressal mechanisms and repair services, which can further foster lack of trust in the quality of service that is provided.

The grid provides AC power and there is a full range of AC appliances

Supply in DC can be an interesting option for off-grid approaches when grid connection is not expected in the mid-term or ever. Most basic appliances operate in DC (*e.g.* LED lights, phones, radios, TV sets, computers) and transformation from AC to DC is avoided, with the associated expense in power electronics and losses. Other efficient DC appliances are becoming gradually available (Phadke *et al*., 2015). DC grids operate at lower voltage levels than AC grids and voltage constraints and losses limit the use of DC to networks of a certain size.

14 For instance, the percentage of energy demand that is served over a period of one year does not provide information about how often essential demands have to be curtailed or about how poor the service is for off-grid solar-based systems during the wet season when solar radiation is low, or for grid-connected systems at the time of the annual peak demand.

Compatibility with the AC grid, if it becomes necessary, is an issue and increases the risk of stranded generation and network assets, as well as the complexity of establishing safety and quality of service standards.

The level of demand that the distributor is committed to supply has no external limits and it can be accurately estimated in an aggregated value

In least developed countries with a serious electricity access problem, there is much uncertainty about the demand level of future consumers that have never used electricity, or that are supplied with a very low reliability level. Despite this, electricity regulatory agencies, electrification planners and private developers must assume some demand level that must be met, now and in the future.

Perhaps the simplest choice is to estimate the demand (and its rate of growth) based on knowledge of other consumers in the region who live under similar conditions. The estimation may include, in addition to basic residential demand, productive or community electricity uses. In other cases, if the available budget is very tight or the affordability of the consumers to purchase additional appliances is severely limited, it might be necessary to define a demand level that is considered to be compatible with a minimum reasonable living standard.[15]

It is important to note the difference between "supply capability" (how much power can be drawn from an outlet) and "affordable consumption" (how much electricity the household can pay for and use with the appliances that can be afforded). Perhaps the ideal target in electrification planning is a level of supply capacity and energy that does not limit the level of electricity demand for services that the household could afford. The number, type and level of service of the appliances in a household –and particularly in households that have recently

15 This minimum standard will depend on the specific region, among other factors. However, it has been proposed that a minimum standard of living requires an electricity access that could provide:

- 300 lux of lighting during at least 4 night hours,
- utilization of radio, TV, cell phone and computer,
- and extension of the life of perishable food by 50% longer than at ambient temperature.

In addition, electricity supply must be affordable and have a minimum level of reliability (electricity is available when needed) and quality of service (voltage level stays within a prescribed range). (Source: Julio Eisman, Acciona Microenergía; personal communication).

received electricity access– mostly depend on the affordability level, rather than on the capacity of the electrical supply.

Another important consideration is that the demand level should be specified in terms of services –*i.e.* lighting, communication, entertainment, space conditioning, power for productive activities or cooking– and not in terms of electrical energy consumption or power. An important reason for that is that the efficiency of the appliances is evolving rapidly and, for instance, it is now possible to provide the same quality of lighting than five or ten years ago with an order of magnitude less of consumption (Phadke *et al.*, 2015).

Regulated tariffs cover the cost of supply and, in particular, the distribution network costs

Perhaps the most important barrier to an orthodox and simple approach to the provision of full electricity access in many least developed countries is the existence of regulated subsidized tariffs, *i.e.* tariffs that cannot recover the total cost of supply. The typical reason for this (in principle absurd) situation is political interference in the process of tariff setting, usually motivated by fear of losing political support if electricity tariffs increase, and the fact that many households are incapable of paying the actual costs or just refuse to do it, even if they can afford to pay. Subsidized tariffs can only be sustained if the distribution companies are publicly owned and the deficit in revenues is somehow compensated with internal transfers of funds from the provincial, state, or national budget. Frequently these distribution companies are highly indebted, which makes it difficult for them to borrow money to extend the service to more consumers. The more consumers they connect, the more money they lose. Paradoxically, these distribution companies are not interested in augmenting their business, as this would only worsen their dire financial situation.

This creates a new regulatory dilemma: Should off-grid supply tariffs charged by independent developers be regulated and, if so, how to establish the off-grid tariffs? Note that the customary rule of a uniform tariff for all households connected in low voltage has to be abandoned here, since the cost of off-grid electrification is typically higher than the average cost of supply, especially if the uniform tariff is subsidized. Developers would only accept the application of a uniform tariff if: i) the initial investment is subsidized so that the regulated uniform tariff is sufficient to meet the operation and maintenance costs permanently; ii) the deficit in income is permanently covered by some guaranteed external fund, either from a donor or some official source, which is a solution fraught with problems.

A component of the tariff –regulated or not– that deserves to be mentioned here is the connection fee, since it constitutes an important deterrent for some potential consumers with very low affordability. The connection fee happens only once, when the new consumer is connected to the main grid or to a microgrid for the first time. The fee charged by distribution companies for connection to the main grid ranges from zero to $400, depending on the country. This amount is often insurmountable for many consumers, who, being close to a low voltage distribution network have to desist from being connected, because they cannot afford the connection fee, see (Maithani and Gupta, 2015: 62). It has been argued that high values of connection fees might be a discouraging measure adopted by distribution companies that do not want to connect more consumers, for the reasons that have been presented already (Tenenbaum *et al.*, 2014: chapter 5).

Theft and non-payments are under control

Illegal connections to the existing grid are very frequent in deprived areas in developing countries. The ensuing loss of revenue, plus the high rate of unpaid bills and technical energy losses in lines and transformers, all contribute to the difficult financial situation that characterizes many distribution companies in developing countries.[16] To these effects one has to add the fact that the residential and agricultural tariffs in many developing countries are established below the actual total incurred cost of electricity supply, as indicated before. The obvious consequence is a disastrous financial situation of the distribution companies.[17]

16 For instance, the state of Bihar, India, reported losses of about 50% for the three concepts together. Typical values in more developed countries could range between 6 and 10%.

17 Absorption of illegal connections into a legal and safe system can be promoted by combining an accurate monitoring of the area, easier bureaucratic procedures, repression of illegality, and affordable service contracts, as shown in Ahmedabad, India, see http://www.wame2015.org/case-study/990/ahmedabad-slum-electrification-project

Energy poverty affects a minority of consumers

Least developed countries exhibit the lowest indicators of socioeconomic development, and they meet three criteria: i) poverty level (measured by the gross national income per capita), ii) economic vulnerability and iii) low level of human development (measured by indicators of nutrition, health, education and adult literacy in the Human Development Index). Most of the population without electricity access live in these countries, with India being an exception, with its significant differences between segments of the population.

The unfortunate implication of having a large fraction of the population without electricity access is that it is not viable to cross-subsidize whatever electrification remains to be done with an uplift in the tariffs of those with access. This is what, in one form or another, was done some decades ago in every country in the world that today is considered to be "more developed". This is also the case today in some countries with a small fraction of population without electricity access, see Box 1, for instance. But it is not possible when the fraction of people to be subsidized is large, since this would pose an unacceptable burden on the remaining consumers. The subsidies have to come from other sources.

Cross-subsidization is implicit and socially is a non-issue, except sometimes for social tariffs

Although cross-subsidization cannot be the solution to the financial gridlock of electrification in countries with a large percentage of potential consumers without access, it can be very helpful in other occasions. For instance, the company Acciona Microenergía provides stand-alone solar systems to about 3,000 households in the mountainous area of Cajamarca, Peru. The company owns the facilities and is responsible for the quality of service indefinitely, as a regular utility. They charge their consumers the same social tariff that applies to the analogous category of grid connected consumers. The deficit in revenues is collected via a small regulated uplift in the general tariff, see Box 1.

Another example is cross-subsidization at local level. Some villages or clusters of population include some loads –such as schools, health centers, small industries, shops, banking outlets or telecommunication towers– that may be willing to pay some extra fee so that a microgrid would be viable for the entire cluster. The entrepreneur could then use some sort of price discrimination: i) poor households would pay a fixed monthly small fee to be able to connect a couple of lights, charge a phone, and perhaps use an efficient radio or TV,[18] with a limiter in the connection point to verify that no excessive consumption takes place; ii) wealthier consumers would have meters and would pay in proportion to their consumption; iii) the "anchor loads" would pay according to a tariff that would make the microgrid economically viable. If such a tariff design is agreed to by all the consumers and achieves the financial viability of the microgrid, the objective has been met. Most villages and clusters of households, though, will probably not meet the requirements, and most of the electrification financial problem will remain unsolved.

DISCUSSION

The two previous sections have shown that the regulation of electrification to achieve universal access in least developed countries cannot be based on the same assumptions that have enabled the prevalent regulatory compact in the more developed countries. Instead, it is clear that a number of open issues exist that must be understood and examined carefully. This section discusses these topics and some preliminary recommendations will emerge from the discussion, which are later outlined in the final section of the paper. The following list of topics will be discussed:

- How to deal with the viability gap?

- Are there viable business models for off-grid supply?

- Should off-grid supply be regulated?

18 Note that, although the monthly fee might be small (*e.g.* $2/month) for poor households, the price per kWh consumed by this segment of the population is the highest for all types of consumers, off –and on– grid. This is correct although counterintuitive, as the charge for the scarce consumption of kWh has to include not only energy, but also other necessary infrastructure investment costs.

- Should off-grid solutions be grid-compatible?
- How to engage the beneficiaries?
- How can electrification be made sustainable?

One more topic is added, to emphasize the need to consider the power system in its totality, beyond the distribution network level, where most of the electrification activity usually concentrates.

Key references are provided, acknowledging the important conceptual contributions that have been made in each one of these topics, but also the huge task remaining of turning them into implementable electrification approaches.

How to deal with the viability gap?

There is an unavoidable iron law of rural electrification and its statement is simple: *Rural electrification needs subsidies.* This is true for every rural distribution network in any country, developed or developing, but the effect is more pronounced when the distribution network has to supply a dispersed, small demand, as is systematically the case in rural areas of least developing countries with scarce or no electricity access (World Bank, 2010).

The cost of building a distribution network from scratch heavily depends on the demand density. If demand is low at each connection point, and the points are widely dispersed, the network cost is much higher (several times more, typically) than the cost of supplying a dense neighborhood in a town. This fact applies both in developed and developing countries. Since in virtually every country in the world the tariffs for consumers connected to low voltage are uniform,[19] regardless of whether the consumer is connected in a rural or urban area, urban consumers

19 In some countries, tariffs are uniform for a given voltage level throughout the country. Other times tariffs are uniform only within the territory that is supplied by the same distribution company. Sometimes the consumers connected at a given voltage level are divided into groups, depending on the level of consumption or the type of meter and the tariff is uniform for all the members of each group.

substantially subsidize rural consumers. This effect becomes even larger for off-grid solutions, since the cost of supply with small off-grid generators that rely on solar, diesel, mini-hydro or biomass technologies, are typically significantly higher than those of centralized power plants.

Basically every country has had to implement some rural electrification program to provide electricity access to some less accessible and poorer areas. In addition, these programs have been subsidized with public funds or by adding an uplift to the tariff charges to already connected consumers (the majority). Once the rural electrification infrastructure has been built and its cost recovery has been guaranteed, the beneficiaries of the program have paid the standard tariff or, sometimes, they have benefited from some social tariff that also applies to those who meet some low income or other requirements. The obvious problem with developing countries with a large percentage of non-electrified population is that the volume of required subsidy to achieve universal electricity access is large, even for the public budget, and it is also too great a burden to be shouldered by the reduced percentage of electrified consumers.

The viability gap can be moderated by trimming the costs, which might be accomplished in different ways: improvements in performance and lower costs of key technologies, like solar panels and batteries for off-grid solutions; reduction of operation, maintenance, or management costs by increasing the size of the company or using automation enabled by ICT technologies; more efficient power system operation, also applicable to microgrids; and lowering technical standards –*i.e.* application of a simplified grid code to rural electrification due to the low density of demand–.

The latter method deserves special attention, since a grid code is very specific to each power system and its application is the outcome of a regulatory decision. An important boost to rural electrification can be achieved if regulators would allow less-rigorous grid standards for grid extension into rural areas with low demand density, as well as for microgrids. Demanding the same electrical and safety standards required for the central grid can be overkill in rural areas. Brazil, for example, has significantly reduced the costs of its rural electrification by establishing standards for rural electrification that maintain system safety but are less onerous and less costly than those in urban areas.[20] The state of Uttar Pradesh in India has established lighter standards in the grid code for rural electrification. While it is important that safety and the integrity of the electrical system be maintained, regulators should specify the least onerous way that this can be accomplished in rural settings.

In general, it is to be expected that these cost reduction methods will not be able to eliminate the viability gap. Therefore, in general, electrification has a serious financial problem that cannot be ignored. There are some shortcuts, but they are not a solution for the general problem:

- Donors –ranging from NGOs to governments or companies of any size– may give away funds in sufficient volume as to cover the financial gap of specific pilots or small projects. This is useful, but insufficient to meet the needs of more than a billion people without electricity access.[21]

- Small private entrepreneurs, acting outside regulation, can interact directly with villages or individual potential consumers and offer them a basic electricity service (the typical two lights and a telephone charger) at some agreed price. Subsidies might be available in some cases –for instance subsidies for the use of solar PV technologies– but, in general, we refer here to the case where subsidies are not used. This type of business model is mushrooming in the poorer regions of India and Sub-Saharan Africa. How is this possible without subsidies? Even very poor potential consumers are willing to pay for electricity at least up to the amount that they are presently paying for lighting of low quality with kerosene lamps and candles, which have negative impacts on health and safety. This amount is enough to obtain a minimum electrification level.[22] The problem

20 The case of grid extension with lower technical standards in agricultural areas in Brazil, by the initiative of the engineer Fabio Rosa, is well known. It is also remarkable that these standards became officially accepted years later in the national grid code for rural electrification once their technical soundness and cost reduction potential had been amply shown, see (Bornstein, 2007).

21 Even the funds pledged to be made available by large programs like Power Africa ($7 billion total) or the European Union, fell very short of the financial needs estimated by the IEA ($48 billion per year until 2030).

22 These households at the bottom of the pyramid happen to be paying per kWh of electricity much more than what everybody else that is connected to the grid is paying, in developing and developed countries. However, these are the most precious first kWh, whose value for the user is higher than any further consumption.

is that the affordability of these consumers is exhausted with this basic service and this minimalist technical solution cannot be scaled to meet higher demand levels, including community and productive uses. Therefore, this is not the approach that will solve the global problem, even if it is providing a much-needed improvement in the quality of life to its beneficiaries.

- Internal local cross-subsidization, in those villages or clusters with enough presence of anchor loads, may achieve financial viability of an off-grid option. Depending on the consumers' mix, the viability gap might in some cases be reduced to zero, but this requires a significant amount of non-residential demand that can afford the cross-subsidy, which is probably uncommon in the considered countries in rural areas.

- An uplift in the tariffs of already connected consumers, once the volume of consumers with access is clearly dominant such that the uplift is politically and socially acceptable.

- Massive subsidies coming from the concerned governments or from strong international cooperation funds if universal access is to be achieved. Note that this is not smart financing (which is always welcome); it is a subsidy (*i.e.* giving money away).

Finally, it must be realized that the investment cost in an electrification project strongly depends on its level of risk, *i.e.*, on the uncertain factors that determine the costs and the revenues of the project. In general, uncertainty raises the cost of capital and blocks investment decisions that would be profitable at lower levels of risk. Uncertainty may arise if the duration of concessions is too short, if there are unexpected changes in tariff levels or other regulations, or if the political environment shifts –for example, possible political decisions such as nationalization could change the ownership of industrial assets–. Uncertainty and risk are an integral part of basically any business project and some risks are unavoidable, but a stable, professional and independent regulator makes investment more attractive, while protecting consumers.

In the following sections some of these risk factors will be discussed, as well as some regulatory practices and other measures to reduce the risk, and therefore the project cost.

Are there viable business models for off-grid supply?

The need for subsidies for rural electrification has been discussed in the preceding subsection on the viability gap. This need is even more acute for off-grid technologies. This has to be explicitly taken into account when trying to define economically viable business models for off-grid electricity supply.

Assuming a source for the subsidy exists, three major sources of risk can be identified for the off-grid solution providers: i) the subsidy fails to reach its beneficiary; ii) the grid arrives; iii) competition from solar kits.

Failure of the subsidy

Investment in electrification should necessarily be a long-term activity, since the physical and economic lifetimes of network-related assets easily reach 40 years or more and they are never or very rarely dismantled.

Firstly, it is unreasonable think that a subsidy will last for that long. Moreover, given the difficult financial situation of many of the distribution companies, it is also difficult to think that the subsidy itself is not at risk from the outset, with the governments deviating the subsidy to their own distribution utilities, instead of respecting the original destiny of these funds. If the investors do not trust that the subsidy will arrive to them on time with whatever established periodicity, and they are subject to some regulated tariff, they probably will decide not to invest. On the other hand, if they have some degree of freedom to set or to negotiate the tariff, they will try to recover their investment with an acceptable rate of return in a short period of time, for instance 4 or 5 years, resulting in high tariffs to be paid by the consumers.

The grid arrives

Most least developed countries have a “two-pronged approach” to electrification: grid extension for most people and microgrids or stand alone systems for remote areas or for those areas where the incumbent distributor does not plan to invest in the near future.

In the absence of specific regulation, micro-grid developers face substantial risk if the central grid reaches the area before the investment costs have been recovered, since they will most likely go out of business as they will lose customers to the lower cost (and typically subsidized) central utility service. This added risk can make power from micro grids costly and unviable, since the financial risk of the project is high and the developers will try to recover the investment costs in a few years, fearing that the arrival of the grid.

The uncertainty for any off-grid investor and the associated risk will be reduced if the country has a set of regulations ready to be applied when the two modes of electrification meet. Regulation should provide an explicit path for isolated microgrids to interact and connect with the central grid (Tenenbaum *et al.*, 2014; OKAPI, 2017; World Bank, 2010).

The competition of the home solar kits

Due to their high performance and low cost, solar kits may successfully compete with the other standalone solar systems as well as with microgrids that only provide basic service. The business model for solar kits is radically different from both the classical utility approach and the approach taken by most off-grid developers, since solar kits do not need a "utility-like" or a centralized firm in charge of operation, maintenance and billing. With solar kits, household electrification is based on an appliance that is bought in a store, easily installed at home, and brought back to the store to be fixed, replaced or expanded. Solar kits, like phones, tablets, or electric shavers, are fully compatible with the AC grid without any adaptation.

Should off-grid supply be regulated?

In countries with low levels of electricity access, off-grid technologies are becoming more commonplace, however they are rarely subject to regulation, except for, perhaps, broad industrial safety codes.

It is long past time to answer a key question: Is lack of regulation an acceptable option for off-grid solutions? Some argue that non-regulated tariffs or other forms of light-handed regulation can promote a more active off-grid sector. No doubt the lack of regulation lowers barriers to entry by removing red tape and technical requirements. Yet, there are also serious drawbacks in some situations and it is important to distinguish where regulation does more good than harm.

On one extreme end, there is the case of stand-alone residential systems, including solar lanterns, light-weight home solar kits, and the standard solar panels with lead acid batteries, occasionally backed up by a small diesel generator for schools, health centers, or medium-size commercial or industrial facilities.

The sale of solar lanterns or solar kits should only be subject to standards that guarantee a minimum level of quality and transparent information to the customer about the expected performance, to avoid that poor people without any technical training or experience buy low quality products for such an essential service unknowingly. Residential solar systems that require some expert installation and maintenance –a utility-like service such as the one provided by Acciona Microenergía in Peru (see Box 1)– may need to be either fully regulated or they can be strictly unregulated and commercially-based, like the one offered by Grameen Shakti in Bangladesh (Wimmer, 2012).

The case of microgrids is different, since the provider can find itself in monopolistic conditions once they are well established in a village or a territory, and unregulated monopolies should be avoided. In this case, some tariff and quality of service regulation are recommendable to ensure that consumers are adequately protected, as a local microgrid does not experience sufficient competition to prevent it from exerting monopolistic power.

However, this regulation does not solve the problem of the viability gap of microgrids. As indicated before, rural electrification, on-grid and especially off-grid, is substantially more expensive than electrification in urban areas with much higher demand density. As previously explained, cross subsidization of rural electrification by existing grid-connected consumers is not viable in countries with a high proportion of the population without electricity access. Some additional regulation is needed in those cases where internal cross-subsidization is not enough to achieve economic viability of off-grid solutions that try to offer a reliable service beyond an extreme basic level.

Sound regulation should establish the means by which the viability gap could be filled, with an acceptable level of risk for the private investors of not being able to obtain a reasonable rate of return. Regulation for off-grid electricity supply should not be a significant barrier to entry for off-grid operators and should not create an unnecessary burden on electricity regulators. In particular, when the supply companies are small, regulation that is time-consuming and costly to comply with could make off-grid electricity businesses unprofitable. Transparent, quick and standardized procedures should be adopted.

Should off-grid solutions be grid-compatible?

A major shortcoming of leaving microgrids unregulated is that the supply technology is typically of such low quality that it is not grid compatible. In those places where connection to the grid is a possibility, this exacerbates the risk for private developers (who will have to remove the assets if grid-connection happens), results in higher costs for consumers (who typically cover the cost of the financial risk of the developers who may want to recover their investment costs quickly), and leads to a waste of material resources.

Grid-compatible microgrids are a special case. They require regulatory support since they are more expensive than the most basic non grid-compatible alternative and are unaffordable for most poor households. Thus, the developers of grid-compatible micro-grids need to be compensated in order to overcome the viability gap. These grid-compatible and predominantly renewable-powered microgrids deserve to be financially supported by regulation for several reasons: a) their assets are less likely to be discarded if/when the grid ultimately arrives, thereby reducing the risk to potential investors (as well as resource waste; b) if the original renewable-powered generation assets remain, they will not be replaced by the grid-connected generation mix, which is predominantly based on fossil fuels in most countries, setting the path for a less carbon-intensive model for the power sector; c) since grid-compatible micro-grids can provide a level of service similar to (or in many cases, better than) that of the existing grid, they reduce the consumer concern that establishing a micro-grid will only delay the arrival of the grid (a not-uncommon concern); and d) in those places that can be eventually reached by the grid, privately financed micro-grids reduce the pressure on the incumbent distribution company to extend the grid, delaying the utility's obligation until they are financially able to fulfill it.

In order to mitigate the risk of a stranded business when the grid connection arrives and to incentivize investment in microgrids, it is necessary to institute an appropriate regulatory framework to mandate compulsory purchase of power into the grid from such micro grids at a tariff to be determined considering depreciation of the microgrid investments, as approved by the appropriate energy regulatory authority. The microgrid developer should have the option to choose one of the following structures to govern its engagement with the incumbent utility: small power distributor (keeping the entire microgrid activity), small power producer (selling the network to the incumbent distributor, but keeping the generation) or buyout of the whole business (Tenenbaum *et al.*, 2014; OKAPI, 2017). See Box 2.

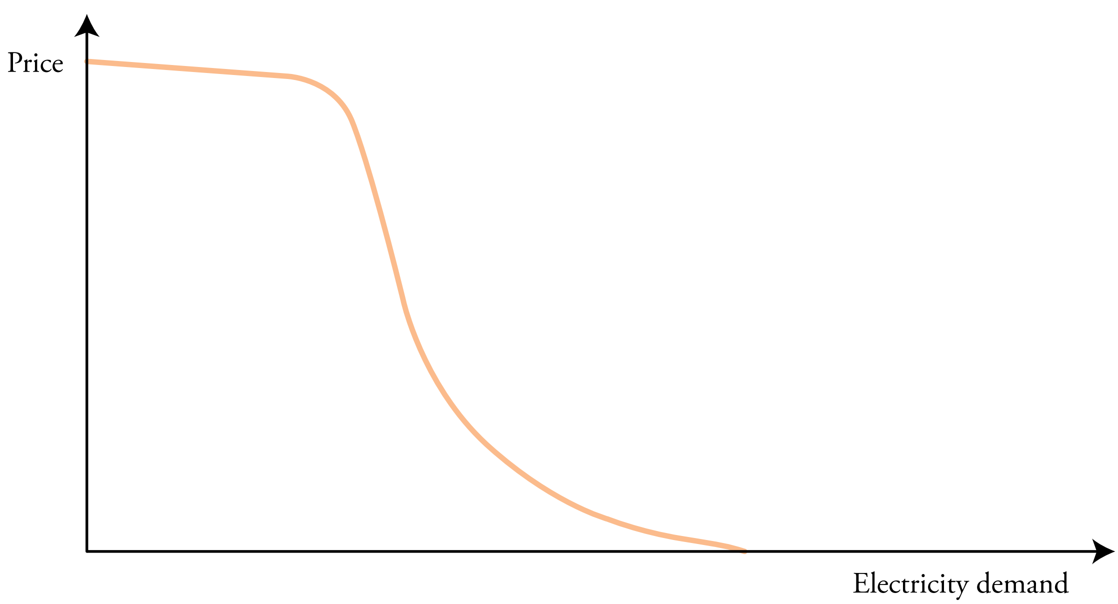
Regulation can prevent the waste of resources that follows from local off-grid systems being built independently, with different technical standards. Where technical standards are uniform, a market for components and replacement develops, facilitating a longer life to electrification projects and lower prices for maintenance. As indicated above, in many cases it is expected that the national grid will be eventually extended to reach isolated mini-grids. If the technical standards are identical or compatible, integration is easy, while if they are not compatible the isolated system may be fully replaced and parts of it abandoned even if not fully depreciated.

How to engage the beneficiaries?

There is just one figure in this paper, purposely, to highlight its importance and the hidden complexity behind its deceptive simplicity. All consumers, wealthy and poor, give a very high value (utility) to the first watt-hours (electric energy) of consumption, the ones that allow them to meet the most urgent needs of lighting, communication, or the creation of a breeze on a hot night. The value decreases for each additional watt-hour used to meet less essential needs (this is just an extreme case of the basic principle of diminishing marginal utility). Not all consumers have the same needs, preferences, and affordability so each consumer has a different curve, however each has roughly the same shape. This curve will evolve over time, as the economic conditions, the new activities allowed by electricity access, and affordability change. Moreover, each curve also depends on the quality of supply. Consumers do not give the same value to a given quantity of reliable watt-hours, which can be used whenever they are demanded, as they give to unreliable electricity supply, which can unexpectedly fail when it is needed most.

This curve (or family of curves) illustrates the difficulty that an electrification planner faces when trying to estimate the demand to be supplied and

Exhibit 1



the willingness to pay of the beneficiaries. Demand level, quality of supply and willingness to pay are inextricably related.

Understanding and forecasting demand is critical to designing the supply of electricity. It is even more so when the potential consumers have not had the experience of using electricity, which happens to be an essential enabling factor for their development, both economically and in other dimensions of life.

How much are the beneficiaries of an electrification project willing to pay? How does that willingness change if a provider offers "perfect" service (*i.e.*, close to 100% continuity of supply, good quality of the waveform, no limit on the amount of power consumed) versus less-than-perfect service? How do we define these imperfect services (*i.e.* the reliability of the proposed service) so that they make sense as real options for the customers to be supplied?[23]

A viable business model must account for the preferences, priorities, social, behavioral, and cultural characteristics of the beneficiaries. Multiple aspects have to be considered: i) the projection of future demand, including the tight interdependence between demand, affordability, and reliability; ii) how to package the "product" (the electricity service) to be offered so that its "reliability" level is understood and actionable by the different stakeholders; iii) game changing technology options and trajectories from the beneficiaries' perspective, like ICT technologies and innovations or home solar kits; iv) implementing social, economic and environmental sustainability; and v) a holistic perspective that combines technology, business models, community engagement, and preferences for use of primary energy resources (Spratt *et al.*, 2016).

Community engagement is a key activity for the success of electrification projects, especially off-grid electrification modes, which are typically more tailor-made

23 The concept of reliability, or quality of electricity supply, is easily grasped in a first approximation, but it is difficult to convey in practical actionable terms that can be understood for a non-expert population. The performance metrics to be used have to be simple to understand, but have to be able to reflect what matters to people (frequency, duration and extent of outages, and when they occur). These metrics have to be integrated in the terms of contracts and in incentives of remuneration mechanisms to be used by regulatory authorities. They should be an essential element in the design of grid-extension plans and microgrids.

and require more interaction with the local communities. The required skills and the time devoted to this activity should not be underestimated, see (ITD UPM, 2017). Successful off-grid electrification solutions are often well adapted to the local context, enhance and leverage existing resources and capabilities, enable the creation of economic opportunities and enterprises, and increase capacity for social organization.

How can an electrification project be made sustainable?

This is probably the most important factor for the long-term success of an electrification project. Sustainability has several dimensions: financial, technical, social, and environmental, all of which are critical. Any electrification plan must have a vocation of unlimited permanence. In this respect, business models should get as close as possible to the "utility model" (*i.e.*, an organization is responsible for the supply with a prescribed or agreed minimum level of reliability, at an efficient cost, forever).

- *Financial*. The financial design of the electrification plan must make sense, from the outset and forever. As indicated before, meaningful electricity access requires subsidies, in the up-front investment costs and also possibly in the future tariffs for those that cannot afford them. This has to be fully accounted for in the specification of the electrification plan.

- *Technical*. Distribution networks, and power systems in general, live forever. While transformers, cables, insulators, protections, and other gear are replaced and upgraded, and new circuits are created, the overall supply system remains. The same should be the case with off-grid supply technologies, whether they are expected to become connected to the grid or to remain isolated. Here the maintenance procedures are critical and they have to be included in the electrification plan and the selection of the supply technology and business model from the outset. Much has been discussed and written on the topic and much can be learned from successful and failed experiences. Different issues are involved here, from the technical capacitation of local people, to the sense of ownership by the community, to the allocation of responsibility to some stable organization with some utility-like characteristics for off-grid solutions.

- *Social*. This is directly related to consumer engagement and preferences. The beneficiaries must accept the business model, both individually and as a community, if the electrification plan is to survive. As a general principle, the higher the engagement of the community, the higher the chances of a sustainable business model. This engagement can be enhanced by the utilization of local energy resources. It can be added that the utility or utility-like models, if well accepted by the consumers, also provide a sound guarantee of social sustainability.

- *Environmental*. The environmental impacts of universal electricity access have been typically neglected, with the implicit assumption that the level of consumption of these new consumers will be so low that the impact on carbon emissions or other local environmental impacts will be insignificant. However, these assumptions have to be reconsidered, as some authors have pointed out recently: a vast number of consumers are expected to reach comfortable levels of electricity demand within a few decades, in addition to the people who are now benefiting from sound access in more developed countries. If the wrong supply technologies are adopted now, it will be very difficult to revert that trend later. Sustainability concerns should be present from the outset on the design board of any electrification plan and they should impact the choice of the adopted solution, both from the point of view of the supply technology and for the choice of business model.

Obviously, one of the potential concerns of the environmental sustainability of universal electrification is climate change. While emissions should not be used as an excuse to deny access to a basic level of electricity, neither should electricity access be planned without regard to the climate implications of growing access and consumption. This is the right time to guide the adoption of a long-term electrification path in developing countries that is based on economically and environmentally sustainable systems, leveraging close cooperation among governments, international organizations, and electricity players.

While a basic level of electricity access should not be sacrificed in the name of carbon emissions, as the emissions are small and the human dignity implications are large, it is increasingly possible that this is a false tradeoff. It is possible to expand electricity access while using low-carbon generation methods, as evidenced by the proliferation of solar-powered microgrids and home systems in India and Africa, and the significant regulatory and financial support from India's government for renewable-powered on and off-grid generation. Incorporating that off-grid generation into the central grid as it expands will not only do a favor for microgrid investors, but also for the climate.

Electrification is much more than the last mile

This paper has focused mostly on the distribution component of electrification, at lower voltage levels, close to the end consumer. However, in the most frequent case of grid connection, when the volume of demand to be electrified is substantial, it is also necessary to reinforce or expand the high voltage distribution network –also named sub-transmission– and the transmission networks, as well as the addition of new generation.

Much has been discussed and written on the failure to deploy sufficient large infrastructures of generation and transmission, without which electrification is greatly encumbered. (Kapika and Eberhard, 2013) and (Eberhard *et al.*, 2016) state that the primary reason for the dismal record of Sub-Saharan Africa's power sector is simply that the region does not generate enough electricity. The lack of sufficient transmission capacity limits the support that trade between countries could contribute to mitigate power shortages. These and other references show that sound regulation (for instance, the use of cost-reflective tariffs), backed by independent regulatory agencies, can provide more revenue certainty and do much to encourage investment. Power planning and timely initiation of competitive tenders or auctions for new capacity are also important. The lack of sound transmission cost allocation rules makes it difficult for the parties involved to reach agreement in the planning and construction of interconnection lines (Rose, 2017). Novel approaches have been proposed recently to mitigate the financial risk of investors in large generation plants by centralizing and standardizing the tendering and contracting processes (Africa GreenCo and The Rockefeller Foundation, 2017).

THE WAY FORWARD

Providing electricity –at a level that allows living with dignity in our time– to 1.2 billion people and to improve radically the quality of service to an additional 2 billion people requires a huge amount of investment, plus the costs of operating and maintaining the new assets. If the reader of this paper lives in a country –or a state in a large country– with, for example, forty million people, all of them with electricity supply, universal electricity access in the long-term –where the non-electrified people today can be assumed to attain a "normal" standard of living– will require thirty times the existing power sector infrastructure in this country of reference.

In today's world economy such a large investment can only be carried out by the private sector, leveraged by public financing and regulatory support. Therefore, this huge electrification effort has to be based on viable business models, which have to be indefinitely sustainable (economically, socially, and environmentally), replacing or replicating what the traditional utilities have done so far everywhere.

These viable business models of electrification must be well adapted to each specific country environment and, in particular, to the regulatory framework that enables them. It has been shown in this paper that this regulation must depart from the well-established practice. It is probably one of the major regulatory challenges of our time, if not the greatest, to determine how to make use of elements of classical regulation while also introducing new features that respond to the very different underlying assumptions in those regions of the world in most need of electrification. In some cases, the measures should just consist of applying the well-known principles and methods that have functioned well in developed countries. Creativity will be needed in other cases in the search for solutions to new problems.

Both grid-extension and off-grid solutions will be necessary, although off-grid assets might end up being often transitory, as in many places the interconnected grid will in the end prevail. Where this is the case, the off-grid infrastructure –if properly designed as grid compatible– can be the support that will ultimately facilitate grid extension and retain local renewable generation resources.

The agents of this transformation could be a multiplicity of small developers, large energy companies that still are only marginally at present in these least developed countries, the incumbent distribution utilities, or combinations of them under different possible formats: parallel operation with total independence from one another, off-grid developers as franchises of the incumbent distributor, licenses given to external large companies to electrify a territory under regulated monopolistic conditions, some form of aggregation of multiple small business models via association or acquisition by a larger firm, or some other approaches, such as rural cooperatives. This is one of the most uncertain aspects of the future electrification process.

Electrification business models must be defined with a permanent provision of service in mind, without an end in sight, as the classical electric utilities were conceived, and with the capability to grow, imposing no limits to the economic development of individual users and communities. This requires paying attention to and demonstrating the technical, economic, environmental, and social dimensions of sustainability. This implies that the future supply costs will be covered for the economic life of the facilities and beyond, that the facilities will be properly maintained without any time limit, and that the environmental impact associated to the production and consumption of electricity will be tolerable.

Economic sustainability requires squarely addressing the "viability gap" issue, *i.e.* how to cover the difference between the true costs (*i.e.* "no subsidies") of electricity supply and the official tariff applied to the consumers, or, alternatively, their willingness to pay for an agreed service with a prescribed reliability level. A large viability gap associated to a given electrification plan will suggest the need for a gradual or "phased" approach, conditioned by financial limits and the need to engage the beneficiaries, at whatever pace it may take.

Good governance and sound regulation do much to reduce investment risk and therefore the cost of capital of an electrification plan. Innovative financing approaches that are adapted to the specific conditions of the power sector in least developed countries can facilitate investment in large infrastructures.

Understanding and engaging the consumers' side at individual and community levels is of essence for the social component of the sustainability of an electrification plan. This is of critical importance for off-grid solutions. Special attention should be paid to the interrelationship between demand level, quality of service, and willingness to pay.

Planning for universal electricity access in countries currently with a low electrification level will entail large numbers of new grid connections. This may require the reinforcement or expansion of the transmission network and the addition of new generation, therefore demanding a complete appraisal of the power system.

Given the scale of the challenge and the diversity of options for electrifying vast regions, effective planning tools are necessary to help governments, electrification agencies, donors and other stakeholders plan and allocate their limited resources wisely, and to reduce the risk for investors and consumers. These tools can be very powerful if they can make use of digital databases of customers and electrical network facilities. They can facilitate the assessment of the economic viability of the business models, –either from the private investor perspective or from a regulatory authority that establishes a remuneration or a tariff for service–.

Due attention should be given to the specific characteristics of the countries where the business models might be deployed: political stability, governance of the institutions, independence of the regulatory authorities, corruption level, and sound energy policy, among others.

A viable business model must be consistent with high level strategic or policy considerations (the "top down viewpoint") for the specific country being considered. High level matters include: i) consistency with priorities in energy policy, *e.g.*, what are the target levels of access? ; ii) climate change implications of the adopted electrification mode and the role that international cooperation could play; iii) the economic value of electricity access and the implications for establishing priorities and allocating scarce resources to different sectors; iv) implications for global security, foreign policy, and energy security in least developed countries; and v) interaction with other drivers of development: water and sanitation, ICT, education, health, agriculture, or transport. The potential contribution of electricity access to development can only be realized if the other enabling factors are also present.

The time is now ripe for the adoption of one or more comprehensive and ambitious approaches, spearheaded by large energy companies in parallel with a multiplicity of local initiatives under some common purpose and coordination, commensurate with the scale of the problem and conscious of the local constraints associated to each specific country and the beneficiary communities. These approaches must be consistent with the global effort towards the use of clean energy technologies, and must be based on a rigorous quantitative assessment of the technical and economic efforts involved, while also including sound measures to overcome the important financial, regulatory, political, technological, managerial, and social barriers that exist.

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CASE STUDIES

Box 1. The experience of Acciona Microenergía in Peru[24]

In the Peru extremely poor mountain region of Cajamarca an interesting new business model has been implemented for stand-alone residential solar home systems. The story initiated in 2008 when Acciona, a large Spanish construction company operating worldwide and expanding into renewable energy, set up Foundation Acciona Microenergìa as its channel for social action initiatives related to basic services. In 2009 Acciona set up an association in Peru called Acciona Microenergìa Perú, acting as a small social service company that provides service in isolated communities. The association started a project called "Luz en casa", installing basic solar systems in 100 small villages scattered in a large territory, and progressively expanded to reach 4,000 households in 2015. Luz en Casa broke even at the end of 2013, charging the equivalent of US$ 3.50 monthly for three lamps and one socket, that is only two thirds of what they paid before for candles, kerosene, and mobile charging. Default rates for this program have been lower than 1%.

In 2010 the Peru Office for electricity tariffs regulation introduced the photovoltaic tariff, which allows the application of the "social" tariff to the electricity users supplied by off-grid solar home systems. A "social" tariff was in force in Peru, as similar provisions are in many countries, to reduce the burden of electricity bills on households in weak economic conditions; its application to isolated systems was an innovation worth considering by many countries.

24 See (https://www.acciona.com/sustainability/society/acciona-microenergia-foundation/).

Box 2. Regulation for grid-compatible microgrids in India

The amendments to India's Electricity Act of 2003 require state regulators to propose regulations for buying power generated by microgrids when they are connected to the main grid. This description does not capture the whole story, however, as the costs of the network and other non-generation components of the microgrid are also significant investments requiring some compensation.

These aspects are, however, addressed in the Forum of Regulators' model regulation in this area. It sets forth a framework in which a microgrid would operate as the franchisee of a utility, with a license and an exclusive right to provide service within their geographical area. The microgrid would be required to charge tariffs that are no higher than the grid's tariffs, which would certainly be below the costs of supply. To reimburse this viability gap, the costs of generation would be subsidized through a Feed in Tariff agreed upon in a Power Purchase Agreement with the incumbent distributor through franchisee fees. Before receiving their license, the microgrid would be required to obtain the consent of the local governing body, after presenting them with a comprehensive plan.

The State Electricity Regulatory Commission would be required to determine the amount of the Feed in Tariff for each renewable generation technology recognized by the Ministry of New and Renewable Energy. The determination of the Feed in Tariff would be through a cost-plus methodology, in which the tariff is set to cover the expected costs of operation plus a rate of return on capital investments, and would thus require only infrequent re-examination. Microgrid operators could request a revision in this tariff if they felt it was unfair. The other costs of distribution and management would be subsidized through a franchisee fee paid by the distribution company to the microgrid operator, determined by mutual agreement of the distributor and the microgrid.

Once the central grid reaches the franchisee, the incumbent distributor is to buy out the franchisee's network assets at book value. The franchisee will continue to own the generation and will continue to sell generated power to the grid at the pre-determined feed-in-tariff.

How the tight oil boom has changed oil and gasoline markets*

Lutz Kilian[1]

Abstract

Starting in late 2008, the U.S. production of tight oil surged, causing a renaissance in the U.S. oil sector that few industry analysts had anticipated. This tight oil boom reduced the dependence of the United States on petroleum imports and allowed it to become a major exporter of gasoline and diesel fuel. Since mid-2014 the global real price of crude oil has experienced a large and sustained decline. This review article addresses several questions of general interest. First, to what extent was the recent oil price decline caused by the tight oil boom? Second, how did the tight oil boom affect the price of gasoline in global markets and in the United States? Third, what determines the investment response of the oil sector to oil price fluctuations? Fourth, how has the tight oil boom affected the transmission of oil price shocks to the U.S. economy? Finally, what are the implications of the U.S. tight oil boom for European oil importing economies?

Keywords: Tight oil; shale oil; oil price; gasoline price; oil investment; real GDP growth.

INTRODUCTION

Starting in late 2008, the U.S. production of tight oil surged, causing a renaissance in the U.S. oil sector that few industry analysts had anticipated. This tight oil boom reduced the dependence of the United States on petroleum imports and allowed it to become a major exporter of gasoline and diesel fuel. It even caused the United States to abandon by the end of 2015 its long-standing policy of prohibiting exports of domestically produced crude oil. It also changed the geopolitical position of the United States, allowing the country to disengage to a larger degree from political conflicts in the Middle East.

As the global price of crude oil declined from about $105 (in December 2016 dollars) in June 2014 to under $50, the question arose to what extent this oil price

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decline was caused by the tight oil boom, along with growing concerns about the continued profitability of U.S. tight oil producers at these much lower oil prices. At the same time, there was much interest in the question of whether the tight oil boom had fundamentally changed the transmission of oil price shocks to the U.S. economy, including the question of whether lower oil prices had been passed-through to lower gasoline prices.

These developments and questions have been discussed in a number of recent studies including Fattouh (2014), Borenstein and Kellogg (2014), Brown *et al.* (2014), Kleinberg *et al.* (2016), Baumeister and Kilian (2016, 2017), Baumeister, Kilian and Zhou (2017), and Kilian (2016, 2017), among others. This review article summarizes some of the key insights emerging from this literature. The article is intended to be accessible to a general audience. Readers interested in more detailed analysis and in the underlying econometric models are referred to the references above.

The remainder of the article is organized as follows. Section 2 explains what the term tight oil (also known as shale oil) refers to, summarizes the quantitative importance of U.S. tight oil production, and provides some institutional background that helps understand how the tight oil boom has affected the prices of oil and gasoline. In section 3, I quantify by how many dollars the tight oil boom has lowered oil and gasoline prices. I stress that the U.S. gasoline price has been determined by the Brent price rather than the WTI price. Thus, the additional decline in the WTI price relative to the Brent price during 2011-2015 caused by the tight oil boom was not passed on to the retail price of gasoline. Section 4 reviews the response of the U.S. economy to the decline in the global price of oil after June 2014, highlighting the role of the tight oil sector. Section 5 examines in more detail the sensitivity of the tight oil sector to oil price fluctuations. Section 6 makes the case for a nonlinear relationship between oil prices and oil investment. Section 7 discusses the implications of the decline in the Brent price of crude oil on European oil importers. The concluding remarks are in section 8.

BACKGROUND

Before addressing the substantive questions raised in the introduction, it is useful to explain what is meant by "tight oil", how this oil differs from other types of crude oil, and what the U.S. tight oil boom refers to.

What is tight oil?

The term tight oil (or shale oil) is commonly used by the oil industry and by government agencies to refer to crude oil extracted by certain techniques that differ from those used in conventional oil production. Conventional oil production is designed to extract crude oil from permeable rock formations. After drilling a vertical borehole, the oil contained in the adjacent rock formations flows into the borehole, where it can be collected and pumped to the surface.

This technique fails when dealing with crude oil trapped in rock formations characterized by low permeability, also colloquially referred to as tight rock. Tight oil producers overcome this challenge by a combination of technological advances. After drilling a deep vertical borehole, they drill horizontally into the tight rock, before hydraulically fracking the tight rock. The latter technique involves pumping a mixture of water, sand, and toxic chemicals under high pressure into the borehole. Under the pressure of this fracking fluid, the tight rock cracks and small fissures open up that allow the oil trapped in the rock to escape and flow into the borehole. The purpose of including sand in the fracking fluid is for the sand grains to keep these rock fissures open, even after the fracking fluid has been removed to be recycled or to be disposed of in separate disposal wells far below the groundwater level. The combination of horizontal drilling and hydraulic fracturing (or "fracking" for short) allows oil producers to access crude oil that geologists knew about for many years, but that heretofore had been inaccessible.

To date, commercial tight oil production has been largely limited to the United States. As with any large scale industrial operation, tight oil production may be associated with environmental damages and other externalities, especially in the absence of a proper regulatory environment. Particular concerns have been the possible contamination of ground water due to improper handling of the fracking fluid as well as an increase in seismic activity in areas near fracking sites. For example, homeowners in parts of Texas and Oklahoma have experienced a sharp increase in the frequency of earthquakes after the expansion of tight oil production. Recent research has determined that these earthquakes were caused not by the fracking activity itself, but rather by oil companies disposing of used fracking fluid as well as other wastewater in disposal wells. If these disposal wells are inadvertently located near fault lines, the risk of earthquakes increases, as the weight of these fluids creates pressures underground.[2]

How different is tight oil from conventionally produced crude oil?

The quality of crude oil can generally be characterized along two dimensions. One is the oil's density (ranging from light to heavy), which is typically measured according to the American Petroleum Institute (API) gravity formula; the other is its sulfur content (with sweet referring to low sulfur content and sour to high sulfur content). Commonly used oil benchmarks such as Brent crude oil or West Texas Intermediate (WTI) crude oil are all sweet and light with an API gravity value of less than 40.[3] In contrast, tight oil consists of light sweet crude with at most 45 API, ultra-light sweet crude with an API of about 47, and condensates with an API as high as 60. The higher the API gravity, the lighter is the crude oil. This means that tight oil is by no means a perfect substitute for conventional light sweet crude oil from the point of view of the refiners that transform this crude oil into the products that firms and consumers buy such as gasoline, diesel fuel, heating oil, or jet fuel. Nor is it a substitute for heavier and more sour

2 The development of tight oil production was preceded by the development of tight (natural) gas (see Mason, Muehlenbachs y Olmstead, 2015; Hausman and Kellogg, 2015). The technology used in tight gas production is similar to that used in tight oil production, which allowed much of the equipment used in tight gas production to be shifted to tight oil production after late 2008, when the U.S. price of natural gas continued to decline.

3 The WTI price is a benchmark that is widely used by oil market participants. It refers to the spot price of WTI crude oil for immediate delivery in Cushing, Oklahoma. The Brent benchmark relates to a similar, if slightly heavier and more sour type of light sweet crude oil from the North Sea that is traded in Europe.

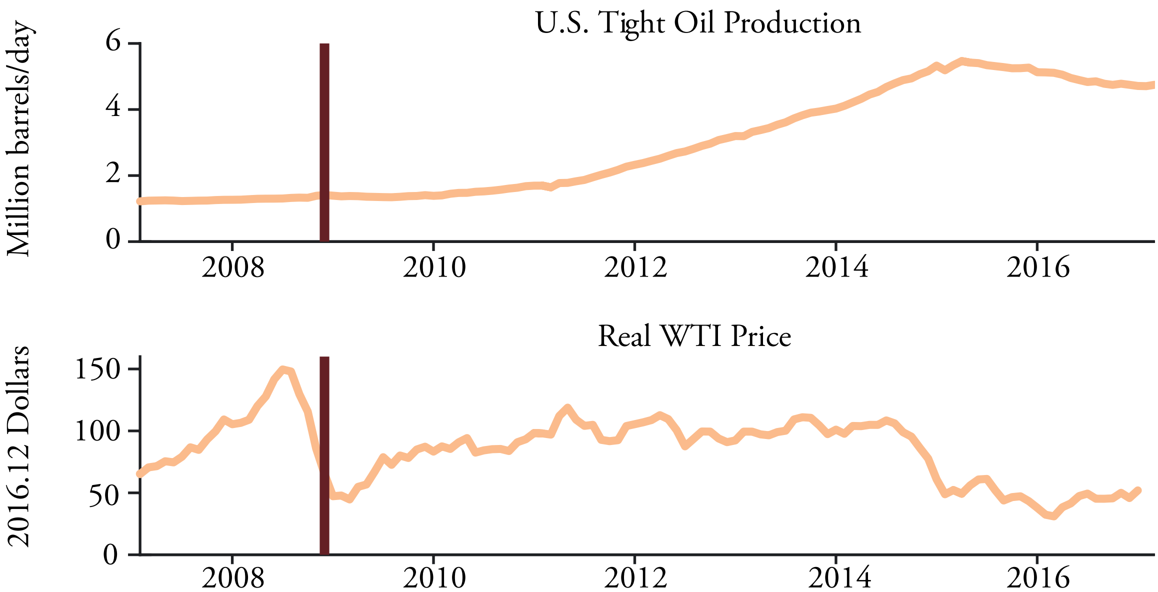
crudes imported from Venezuela, Mexico or Saudi Arabia or the heavy crudes produced from oil sands in Canada favored by some U.S. refineries. This means that statistics measuring total oil production by aggregating the barrels produced of different types of crude oil have to be taken with a grain of salt. It also means that supply-demand imbalances may vary across different segments of the oil market and that different types of crude oil need not be subject to the law of one price, even after accounting for transportation costs. The evolution of the price of oil in recent years can only be understood by keeping in mind these differences across different types of crude oil, because not all U.S. oil refineries are capable of processing the very light sweet crude oil that makes up much of U.S. tight oil production. Before discussing the effect of the tight oil boom on the price of oil, however, it is useful to quantify the surge in tight oil production and, as a result, in total U.S. oil production.

The U.S. tight oil boom

The upper panel of Exhibit 1 shows the evolution of the average daily U.S. production of tight oil since January 2007. Between November 2011 and March 2015, U.S. tight oil production increased by a staggering 287%. Exhibit 1 shows that the tight oil boom is far from over. Notwithstanding a 15% decline from its peak level, as of early 2017 production remains very high. The lower panel shows the spot price of WTI crude oil (expressed in December 2016 dollars to control for inflation), which is a commonly used benchmark for oil market participants. Of particular interest is how slow tight oil production has been to respond to the decline in the real WTI price since June 2014. This resilience is explained by a combination of remarkable gains in productivity and aggressive cost cutting, which allowed tight oil producers to remain in business at far lower oil prices than analysts thought possible in June 2014. Although the number of bankruptcies in the industry increased sharply and although there have been mounting signs of financial stress, as many tight oil producers found it more difficult to borrow, the industry as a whole weathered the oil price decline largely intact. Much of the burden of the adjustment fell on companies providing support services to the oil industry.

Exhibit 1

U.S. tight oil production and the real WTI price, 2007.1-2017.2



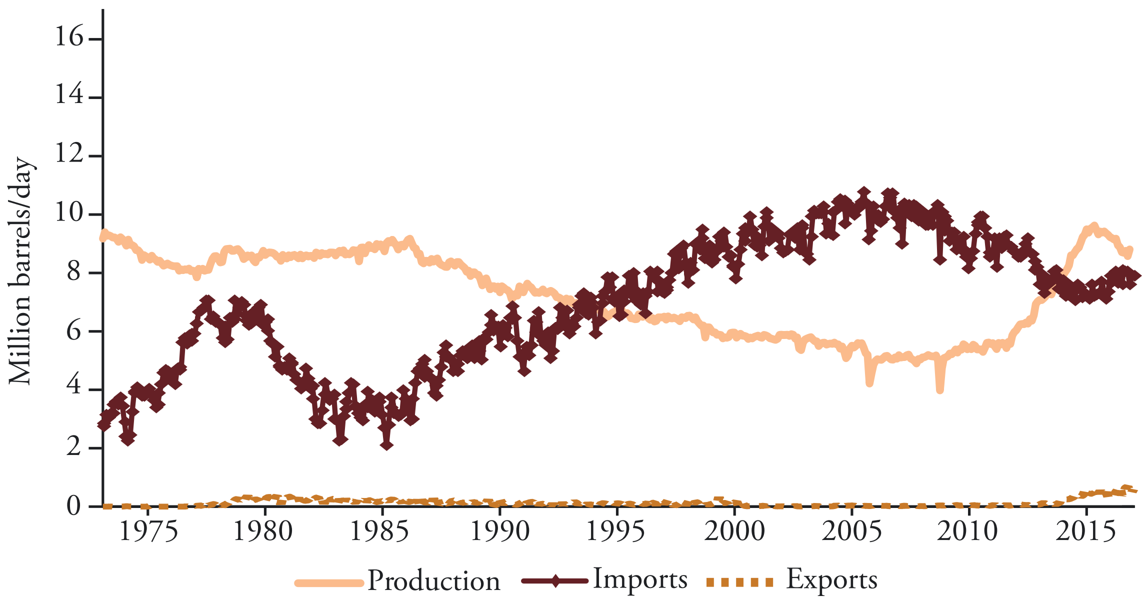
Note: The tight oil production data are obtained from U.S. Energy Information Administration's *Drilling Activity Report* by adding crude oil production in the seven largest U.S. tight oil producing regions, which account for more than 90% of U.S. tight oil production. The vertical line marks the beginning of the U.S. tight oil boom in November 2008.

Source: *Drilling Activity Report,* U.S. Energy Information Administration's.

As Exhibit 2 shows, the tight oil boom that started in November 2008 helped reverse a long-standing decline in U.S. total oil production, defined to include both tight oil and conventional crude oil. By March 2015, total U.S. oil production had reached levels not seen since the early 1970s, allowing the oil sector to substitute domestic crude oil for oil imports from African oil producers, in particular, and to a lesser extent from Arab oil producers. Moreover, after 2014 an increasing volume of U.S. tight oil production was being exported. Although the long-standing U.S. ban prohibiting exports of domestically produced crude oil (with some exceptions mainly for exports to Canada) remained in effect until the end of 2015, in 2014 and 2015 the Obama administration approved an oil swap with Mexico as well as limited exports of crude oil to alleviate the glut of domestically produced tight oil, before the ban was finally lifted altogether in January 2016.

Exhibit 2

U.S. total oil production and trade, 1973.1-2016.12



Source: *Monthly Energy Review,* U.S. Energy Information Administration's.

THE RESPONSE OF THE PRICE OF OIL TO THE TIGHT OIL BOOM

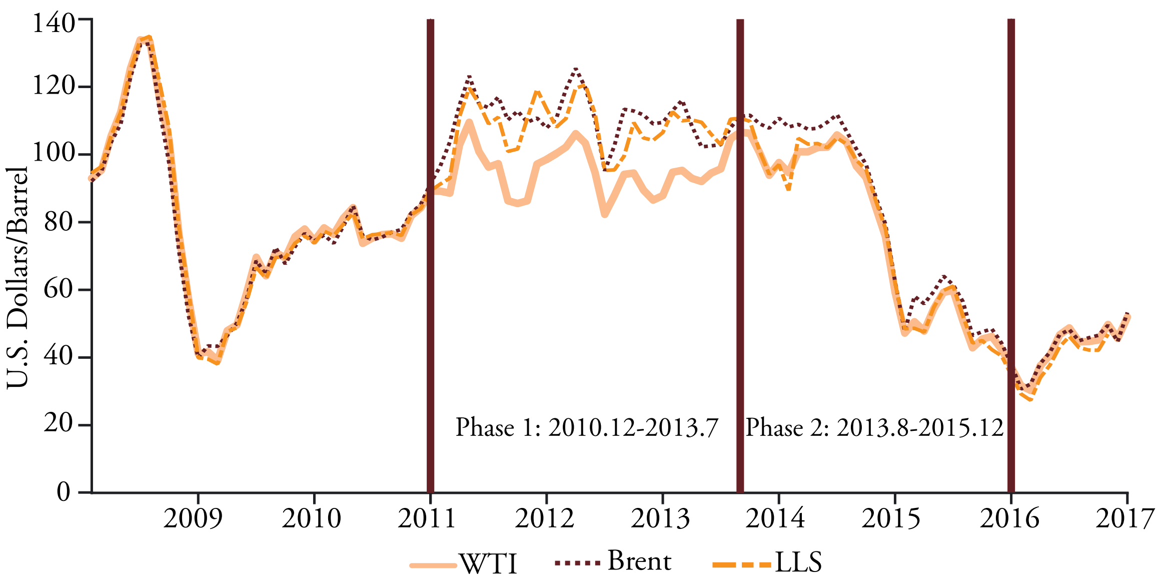
The tight oil boom was facilitated by the use of horizontal drilling and fracking. Although these techniques had been used before, one at a time, their combined use is a fairly recent technological innovation. The tight oil boom is a classical example of a technological shock causing an exogenous shift in the supply of a good. By October 2016, U.S. tight oil production had increased to 6% of world oil production. Thus, one would expect the tight oil boom, all else equal, to have lowered the global price of crude oil. The question is by how much. In discussing the effect of the U.S. tight oil boom on the price of oil, it is important to distinguish between its effect on the global price of oil (as measured by the spot price of Brent crude oil) and its effect on the U.S. price of oil (as measured by the spot price of WTI crude oil).

How the tight oil boom affected the WTI price relative to the Brent price

Exhibit 3 shows the evolution of three benchmarks for the price of light sweet crude oil. The Brent price may be viewed as a proxy for the global price of crude oil. The WTI price is a measure of the price of crude oil at the hub of U.S. oil trading in Cushing, Oklahoma. Finally, the price of Louisiana Light Sweet (LLS) crude oil refers to the price of oil locally produced along the coast of the Gulf of Mexico and traded in Louisiana. Traditionally, these three prices have been moving largely in step. This pattern persists until the end of 2010 and resumes in early 2016. Between 2011 and late 2015, however, there is an interlude during which some of these prices differed substantially. During phase 1, which lasted from December 2010 to July 2013, WTI oil was trading at a steep discount relative to Brent. LLS oil, in contrast, was trading much closer to international benchmarks such as Brent. This pattern changed in phase 2, which lasted from August 2013 to December 2015. Whereas WTI oil still traded at a discount relative to Brent, albeit less so over time, during this phase the LLS price began to track closely the WTI price rather than the Brent price.

Exhibit 3

Monthly spot prices of crude oil, 2008.1-2016.12



Source: U.S. Energy Information Administration.

This pattern is no accident. It reflects changes in oil market fundamentals caused by the increasing availability of tight oil in Cushing, Oklahoma, after 2010. In a nutshell, the problem was that more tight oil arrived in Cushing than could be processed by refiners locally. Traditionally, oil had been shipped north by pipeline from the oil tanker terminals on the Gulf Coast to Cushing, not from Cushing south to the Gulf Coast refineries. These pipelines are in essence one-way streets because oil in the pipeline can flow only in one direction. Nor was there enough capacity for shipping the tight oil to the Gulf Coast by rail. Because there was no pipeline or other transportation infrastructure in place to move the tight oil from Cushing south to the U.S. refineries on the Gulf Coast or east to the U.S. refiners on the East Coast, local supply exceeded local demand and the price of light sweet crude oil in Cushing, Oklahoma, dropped relative to international benchmarks such as Brent. In contrast, LLS oil on the coast directly competed with imported Brent oil, allowing local oil producers to charge the same high price that refiners along the Gulf coast payed for imported Brent crude oil. Thus, the global oil market had fragmented. The central United States formed one oil market, and the rest of the United States remained part of the global oil market.

This situation changed in mid-2013 as a result of two developments. One was that an existing pipeline that used to transport oil from the Gulf ports to Cushing was reversed and that new pipelines linking Texas refineries to tight oil producers were constructed, allowing the tight oil arriving in Cushing to be moved to the Gulf Coast. The other development was that rail transport of tight oil surged. By 2013, nearly twice as many carloads of crude oil were transported by rail than in 2012 and more than 40 times as many as in 2008 (see Esser, 2014). Likewise, the shipping of crude oil by barge both down the Mississippi and along the U.S. coast surged. A combination of rail and barge shipping allowed tight oil production to reach the refineries along the East Coast, which were better prepared for processing light sweet crude oil than the refineries in Texas, which specialized in processing heavier crudes. The surge in the availability of light sweet crudes along the Gulf Coast meant that LLS producers now had to compete against low cost oil from the interior of the country rather than high-priced Brent oil and had to acquiesce to the lower WTI price. In short, what used to be a local glut of oil in Cushing now was transformed into a nationwide glut in the United States, fueled by the tight oil boom.

A potential solution might have been to export this tight oil, given that global demand for crude oil remained high, as evidenced by the higher Brent price. This solution was not feasible. One reason was the existence of a U.S. law prohibiting the export of domestically produced crude oil (with some exemptions at the discretion of the Department of Commerce). This oil export ban had been enacted in 1975, after the 1973/74 oil crisis, in an attempt to insulate the United States from foreign oil price shocks. It is not clear, however, whether the oil transportation infrastructure would have sufficed for large scale exports, even in the absence of the oil export ban. In the end, market participants came up with a less direct solution, which involved refiners purchasing more oil than was needed to satisfy domestic U.S. demand, to refine this oil, and to export the refined products to Europe and Latin America. This approach was perfectly legal because exports of gasoline and diesel were not covered by the U.S. ban on crude oil exports.

The reason why the gap between the Brent price on the one hand and the prices of WTI and LLS on the other gradually closed was twofold. One the one hand, increased U.S. tight oil production over time displaced crude oil exports from Arab oil producing countries, reducing demand for oil in the rest of the world and lowering the Brent price, because the United States no longer relied as heavily on crude oil imports. On the other hand, U.S. exports to the rest of the world of refined products made from domestically produced crude oil caused other countries to cut back on their crude oil imports as well, lowering global demand for oil even further. The downward pressure on the Brent price of oil in conjunction with the upward pressure on the WTI price, as refiners processed ever larger quantities of tight oil, eroded the Brent-WTI price spread in the second half of 2014 and in 2015. By the end of 2015, the U.S. oil export ban was lifted, helping to reestablish arbitrage between the U.S. oil market and the global oil market, with arbitrage being constrained only by the remaining bottlenecks in transporting oil.

An interesting question is why the oil export ban was lifted so late. The answer is that refiners had aggressively lobbied for the continuance of this ban, as long as the WTI price remained below the Brent price. The reason is simple. Because domestic oil could be purchased below world market prices, refiners could produce gasoline and diesel at lower cost than their foreign competitors, which gave them a competitive advantage in the global gasoline market. The gap between the Brent price and the WTI price rose and fell over time, depending on whether transportation and refining capacity was able to keep up with additional tight oil production or not. When the Brent-WTI spread finally all but vanished by late 2015, so did the refiners' resistance to lifting the oil export ban. For all practical purposes, the ban had ceased to be economically relevant.

One might have thought that U.S. refiners would have passed on their cost savings to U.S. consumers of gasoline and diesel fuel, as long as the Brent price exceeded the WTI price. This did not happen. One explanation is that the marginal barrel of oil purchased by refineries on the East Coast remained high-priced Brent crude oil (see Borenstein and Kellogg, 2014). A complementary explanation is that, as long as the gasoline intended for the domestic market may be sold abroad for a higher price, it makes no sense for a profit maximizing refiner to lower the price of gasoline in the United States (see Kilian, 2016). In other words, the U.S. gasoline price was determined in global markets, whereas the price of crude oil during 2011-15 was not. The resulting economic surplus was almost entirely appropriated by the refiners. The U.S. price of gasoline ultimately declined only to the extent that the Brent price of oil declined. Brown *et al.* (2014) make the case that lifting the oil export ban is likely to lower further the price of gasoline by 1.7 to 4.5 cents per gallon, reflecting the increased efficiency of U.S. refinery operations, but it may be several years before these gains are realized.

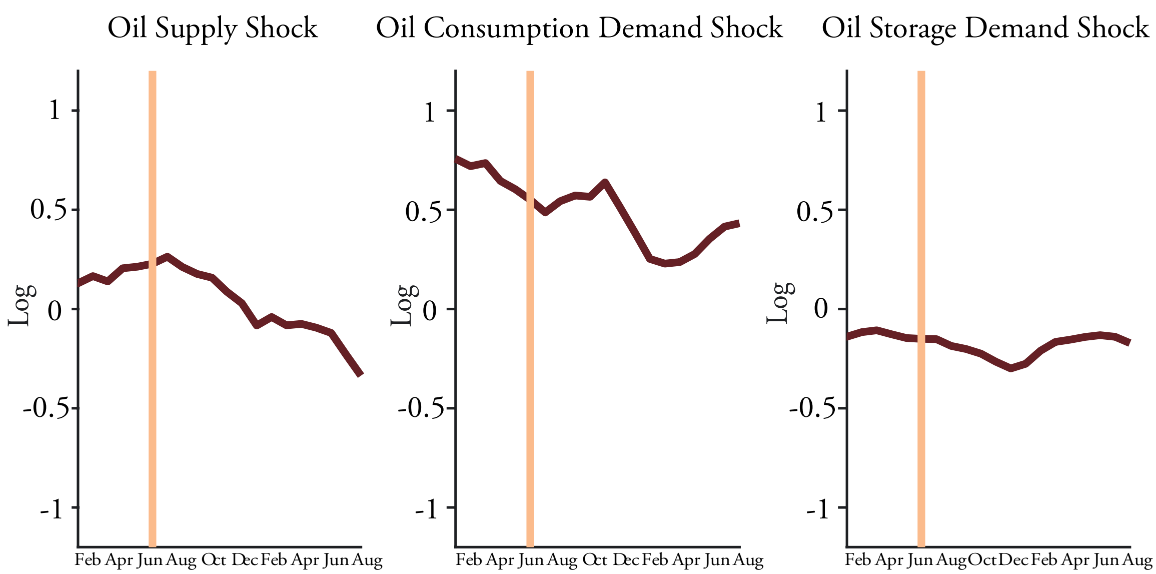
How the tight oil boom has affected the Brent price

The most striking pattern in Exhibit 3 is not the closing of the gap between the Brent and the WTI price, but the steep and sustained decline in all oil prices, including the Brent price, after June 2014. It may be tempting to think that this decline was caused primarily by the tight oil boom, but this is not the case. A recent econometric study by Kilian (2017) shows that the cumulative decline in the real price of oil since June 2014 has been driven by a combination of positive oil supply shocks, negative shocks to the storage demand for oil reflecting expectations of lower oil prices, and negative shocks to consumption demand associated with an unexpected slowing of the global economy.

Exhibit 4 quantifies the cumulative effect of each type of shocks on the real price of oil since January 2014. The results in Exhibit 4 corroborate those in Baumeister and Kilian (2016) based on a different methodology. Baumeister and Kilian provided independent evidence that a slowdown in the global demand for oil was a major contributor to this specific oil price decline in addition to a mix of shocks to actual and/or expected global oil supplies prior to July 2014 and a shift in oil price expectations in July 2014. They also were able to reject beyond a reasonable doubt the common notion that the decline in the price of oil in December 2014, in particular, was triggered by the announcement that Saudi Arabia would not reduce its oil production. There is no indication that market

Exhibit 4

Cumulative effect of oil demand and oil supply shocks on the real price of oil, 2014.1-2015.8



Notes: The underlying structural model is constructed as in Kilian and Lee (2014), except the estimation sample has been updated to August 2015 (see Kilian, 2017). The real price of oil is expressed in log deviations from the long-run average real price of crude oil. Each subplot shows the extent to which the shock in question moved the real price of oil up or down since January 2014. The vertical line marks June 2014. All three shocks contributed to the decline in the real price of oil after June 2014, especially shocks to oil supply and oil consumption demand.

Sources: Kilian and Lee (2014) and Kilian (2017).

participants were surprised by this announcement and responded by selling off oil stocks. Rather this decline coincided with a sharp drop in global real economic activity.

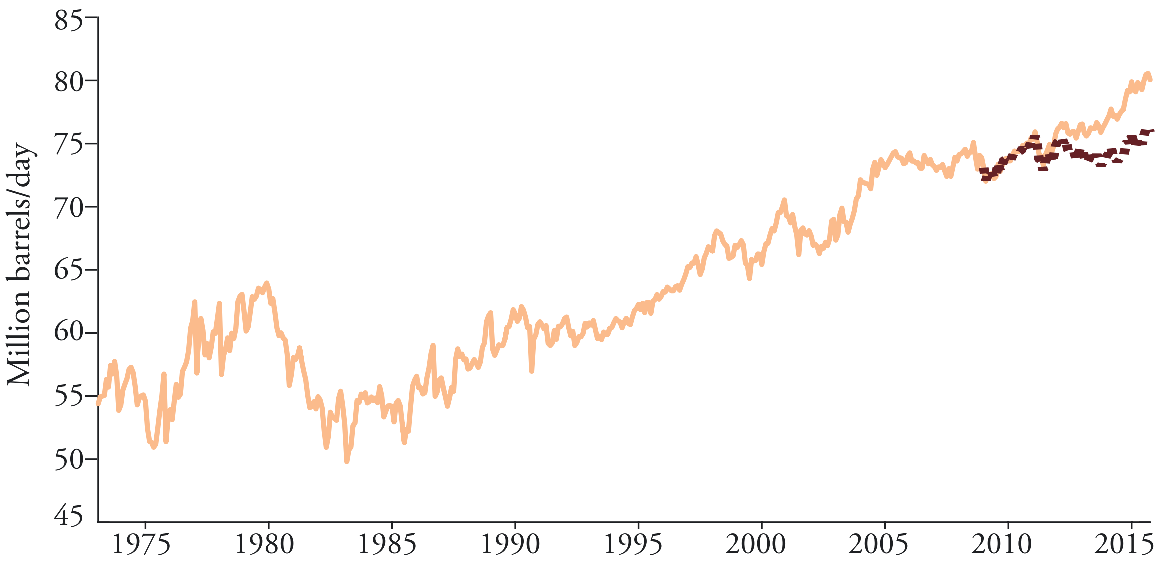
Exhibit 4 highlights that oil supply shocks played an important role in explaining the decline in the real price of oil since June 2014, but these oil supply shocks reflect unexpected changes in oil production worldwide and cannot simply be attributed to the tight oil boom. Although the United States were responsible for some of the global oil production increase since 2008, accounting for a cumulative increase of 4.3 million barrels per day (mbd) by September 2015, there have also been notable production increases in Iraq (2.07 mbd), Saudi Arabia (1.23 mbd), Russia (0.79 mbd) and Canada (0.73 mbd) that were unrelated to the tight oil boom (see Kilian, 2017).

Thus, if we want to assess the effect of the U.S. tight oil boom on the Brent price of oil, we need to decompose the results in Exhibit 4 further. The question of interest is how different the Brent price of crude oil would have been, if all oil producers other than the United States had maintained their observed oil production levels, but the U.S. tight oil boom had never happened. This counterfactual level of global oil production may be constructed simply by subtracting U.S. tight oil production after November 2008 from the observed level of global oil production, as shown in Exhibit 5. Given that the tight oil boom reflected oil supply shocks driven by technological innovation, it is natural to think of the causes of this boom as a sequence of oil supply shocks between November 2008 and August 2015.

Given a suitable structural model of the oil market such as the model proposed by Kilian and Lee (2014), we may then infer the sequence of oil supply shocks required to produce the counterfactual path of oil production, holding constant the remaining structural shocks in the model. Provided this counterfactual shock sequence does not differ systematically from historical shock sequences, we can feed these supply shocks into the structural model to determine how much higher the price of oil would have been after November 2008 under the counterfactual than actually observed. This exercise was conducted in Kilian (2017). The results

Exhibit 5

Actual level of world oil production and counterfactual level in the absence of the U.S. tight oil boom



Note: The counterfactual level of world oil production is obtained by subtracting U.S. tight oil production from global oil production, as reported in the U.S. Energy Information's, *Monthly Energy Review,* starting in November 2008.

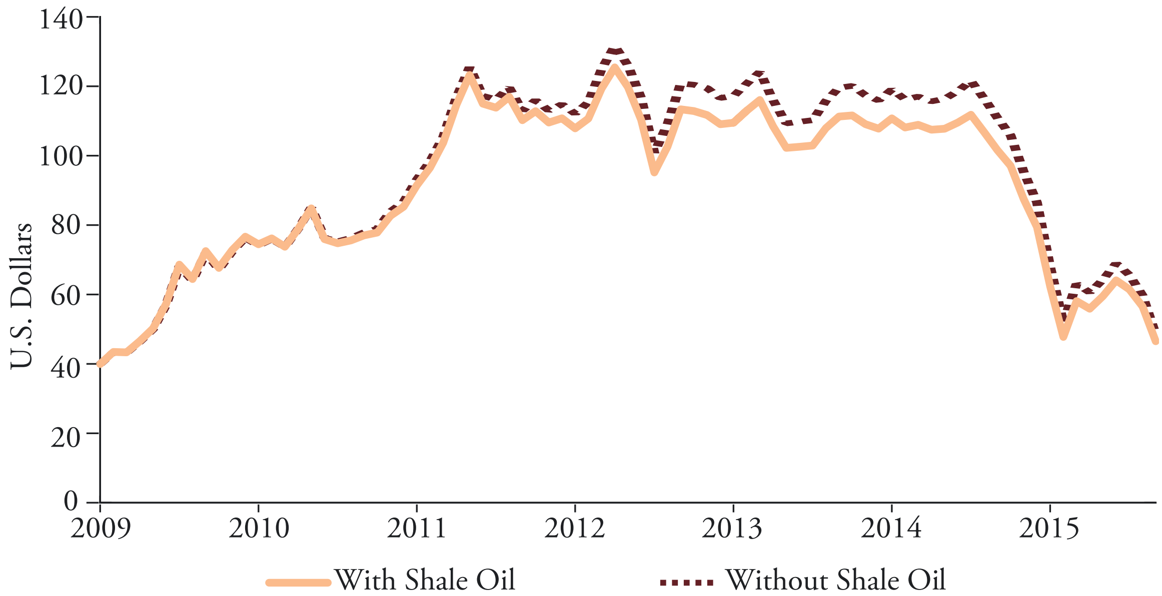
Source: *Monthly Energy Review*, U.S. Energy Information's

are summarized in Exhibit 6. Exhibit 6 shows that the cumulative effect of the tight oil boom on the Brent price started building gradually after 2010 and reached a peak in mid-2014, before declining in late 2014. Whereas in mid-2014 the Brent price was lower by $10 than it would have been in the absence of the fracking boom, by mid-2015 this price differential had fallen to $5.

Exhibit 6 also demonstrates that a very similar price decline would have occurred between July 2014 and January 2015 even in the absence of increased U.S. tight oil production, implying that increased U.S. tight oil production was not the main cause of this price decline. This point is important because it implies that the effect of the tight oil boom on the global price of gasoline and therefore on the U.S. price of gasoline has been quite limited, especially after June 2014.

Exhibit 6

The impact of tight oil production on the Brent price of crude oil



Note: The counterfactual Brent price is based on estimates in Kilian (2017).

Source: Kilian (2017).

HOW THE TIGHT OIL BOOM AFFECTED THE U.S. ECONOMY

Although the tight oil boom was not the main cause of the decline in the global real price of oil that took place after June 2014, the U.S. oil sector played an important role in the transmission of this oil price decline to the U.S. economy.

The traditional view

The traditional textbook view has been that an unexpected decline in the price of oil should stimulate real GDP growth in oil-importing economies. The main channel of transmission is not so much that oil price declines lower the cost of producing domestic goods and services. In fact, few industries other than refineries depend heavily on the cost of crude oil, and the oil share in real GDP tends to be small. Nowadays much of the oil consumed is used for transportation in the form of oil products such as gasoline, diesel fuel or jet fuel. As Baumeister and Kilian (2017) show, however, even the U.S. commercial transportation sector (trucks, railroads, airlines) has been hardly affected by the recent oil price decline.

Instead, the main channel of transmission is that consumers end up spending less of their income on motor fuel at the gas station. As the global price of crude oil falls, so does the price of gasoline. Given a cost share of crude oil in producing gasoline of about 50%, a 68% cumulative fall in the price of crude oil, for example, would be expected to cause a 34% cumulative decline in the price of gasoline, approximately. Lower gasoline prices in turn reduce the amount of money consumers spend on gasoline. To the extent that this money is used to pay for imports of gasoline (or imports of crude oil from which the gasoline is produced), the reduction in gasoline prices reduces the transfer of domestic income abroad. This income now becomes available for additional domestic purchases and stimulates domestic private consumption (see, *e.g.*, Baumeister, Kilian and Zhou, 2017). As private consumer spending increases, so does business fixed investment by the non-oil sector. Increased spending in turn stimulates real GDP, if there is slack in the domestic economy.

Why the investment spending by oil producers matters

Recent research has shown that in countries with a sizable domestic oil production sector such as the United States these stimulating effects may be offset by the response of the oil sector. The concern is not the contribution of the domestic oil production to domestic value added, which tends to be small, but rather the investment decisions by oil producers. Baumeister and Kilian (2017) document a 48% cumulative decline in the investment by the U.S. oil sector (including tight-oil producers) between June 2014 and March 2016. Even after taking account of the small share of oil investment in U.S. real GDP, this reduction in spending has important implications for aggregate spending and economic growth.

Table 1 shows that the cumulative effect on U.S. real GDP growth of the reduced oil investment spending is almost as large as the combined effect of higher private consumer spending and higher non-oil investment spending. The net stimulus for the U.S. economy of 0.17% over seven quarters is essentially zero.[4] Put differently, lower oil prices account for an increase in average U.S. real GDP growth at annual rates of only about 0.1 percentage points. In interpreting these estimates, it should be kept in mind that one of the reasons for the low real price of oil has been the slowing of the global economy, which is reflected in much slower growth in U.S. non-petroleum exports. Controlling for this economic slowdown, average U.S. real GDP growth would have been higher by about 0.4 percentage points at annual rates, but even that estimate is quite modest, highlighting the importance of oil investment spending for the U.S. economy.

Table 1

The net stimulus from unexpectedly lower real oil prices, 2014Q2-2016Q1

Effect on U.S. Real GDP of	Percent of Cumulative Real GDP Growth
Private Consumption	0.51
Oil-Related Private Nonresidential Investment	-0.57
Non-Oil Related Private Nonresidential Investment	0.19
Petroleum Trade Balance	0.04
Net Stimulus	**0.17**

Notes: The estimates of the stimulus have been adjusted based on a marginal import propensity of 0.15 and take into account the share of each expenditure component in real GDP. The response of private consumption and non-oil related private nonresidential investment was estimated based on the regression model that takes into account the change in consumers' purchasing power, as the real price of oil fluctuates, as well as changes in the dependence of the U.S. economy on imports of gasoline and crude oil.

Source: Own elaboration.

4 Unlike the corresponding estimates reported in Table 8 of Baumeister and Kilian (2017), the estimates in Table 1 explicitly account for changes in the dependence of the U.S. economy on imports of crude oil and gasoline (also see Baumeister, Kilian, and Zhou, 2017). The results are, nevertheless, quite similar.

Other channels of transmission

In contrast, a number of other channels by which the oil sector might affect the rest of the U.S. economy do not appear to be nearly as important as sometimes believed. For example, Baumeister and Kilian (2017) found no evidence that the retrenchment of the oil sector reduced investment spending in other sectors of the U.S. economy. Nor is there any evidence that bad loans to the oil sector undermined the health of the banking system. Perhaps most interestingly there is no evidence that the decline in the real price of oil caused a large increase in unemployment, as oil workers lost their jobs. This is true even in oil-states such as Texas or North Dakota. Table 2 shows that despite a significant reduction in the share of mining jobs in employment, in five of the seven U.S. oil producing states, including the main tight oil producing regions, unemployment fell and in the other two it increased only slightly. For example, the unemployment rate in Texas fell from 5.1% in June 2014 to 4.3% in March 2016, which is below the national average, and in North Dakota, the unemployment rate only increased from 2.7 to 3.1%. It can be shown that this result is not an artifact of oil workers migrating to other states. Rather it appears to be an indication of these workers having been reintegrated in the job market.

Table 2

Changes in labor market indicators in U.S. Oil-Producing States, 2014.6-2016.3

	Unemployment Rate (%)	Share of Mining and Logging Jobs in Employment
Alaska	-0.4	-0.4
Montana	-0.3	-0.5
New Mexico	-0.6	-1.0
North Dakota	0.4	-2.5
Oklahoma	-0.1	-0.9
Texas	-0.8	-0.7
Wyoming	1.0	-2.1

Source: Computed based on U.S. Bureau of Labor Statistics data.

Similarly, there is no evidence that the underutilization of capital in oil-producing states had important effects on real GDP growth. Underutilization arises when equipment sits idle because production stops. For example, the number of U.S. oil rigs is down by 75% compared with October 2014, and petroleum rail car loads have dropped by 30% since September 2014. There is also anecdotal evidence of widespread underutilization of motels, restaurants and other infrastructure servicing oil workers. An economy using less capital by construction will produce less real output. One way of capturing these effects is to compare real GDP growth in the United States to the growth rate obtained after excluding the seven oil-producing states listed in Table 2. As Baumeister and Kilian (2017) show, this difference is only 0.05 percentage points of average U.S. growth at annual rates, suggesting that these effects are negligible.

HOW SENSITIVE IS INVESTMENT IN THE TIGHT OIL SECTOR TO OIL PRICE FLUCTUATIONS?

Table 1 highlights that the negative response of fixed investment in the oil sector has been the main reason why the U.S. economy did not grow as much as one would have expected based on the consumption and non-oil investment stimulus. A question of obvious interest is what determines investment decisions in the oil sector in general and in the tight oil sector in particular. Although there is a perception that investment spending by tight oil producers is more price-sensitive than investment spending by conventional oil producers, evidence in Baumeister and Kilian (2017), who compared the 2014-2016 episode with the large and sustained oil price decline of 1986-1987, suggests that oil investment spending, if anything, has become less responsive to oil price declines during the tight oil boom.

There is no doubt that the production of tight oil may respond more quickly to oil price increases than conventional oil production. These arguments do not necessarily extend to investment decisions in the oil sector, however. The decision to continue to invest in new tight oil production depends on whether the expected price of oil exceeds the long-run marginal cost of oil production. If so, oil production remains profitable and investment continues. Otherwise, investment ceases. One difference from conventional oil production is that the marginal cost of producing tight oil tends to be higher than that for conventional oil production, which, all else equal, suggests that, as the expected price of oil declines, investment by tight oil producers should cease before conventional oil investment.

Another difference, however, is that investment in the tight oil sector has a much shorter horizon. Whereas production from conventional oil wells may continue for 50 years, much of the tight oil is extracted in the early stages of fracking, followed by a few years of greatly diminished production. Thus, the investment decision of tight oil producers depends on the expected evolution of the price of oil in the short run only. For new conventional oil investment, in contrast, the price of oil expected at longer horizons also matters. For example, expectations of a longer-term price recovery would tend to make conventional oil investment more robust to oil price declines than tight oil investment. Which type of investment is affected more therefore is ambiguous, in general. In addition, it has to be kept in mind that the uncertainty about the future price of oil may be higher in the short run than in the long run, which would slow investment in tight oil compared with longer-term oil investments. If oil price uncertainty is lower in the short run than in the longer run, in contrast, tight oil investment would be boosted relative to investment in conventional oil.

Finally, we need to remind ourselves that many conventional investment projects (as well as high-cost unconventional investment projects such as deep-sea oil drilling) have long gestation lags. To the extent that these projects were started many years ago, what matters in the current environment is whether these projects would be profitable, if completed. That completion time may be quite short, not unlike that of tight oil investment projects. Costs that have already been sunk into these projects do not affect the decision whether to complete the project, making a comparison with tight oil projects even less straightforward. For all these reasons, it is not clear a priori whether tight oil investment is more responsive to oil price fluctuations than other oil investment.

IS THE TRANSMISSION OF OIL PRICE SHOCKS NONLINEAR?

There is a large literature on nonlinearities in the transmission of oil price shocks to the U.S. economy. Many of the conventional economic explanations of such nonlinearities lack strong empirical support (see, e.g., Kilian and Lee, 2014; Baumeister and Kilian, 2017; Kilian and Vigfusson, 2017). The analysis of the oil price decline after June 2014 suggests that the response of the U.S. economy to unexpectedly low oil prices may be nonlinear for a very different reason. That reason is that the fixed investment by the oil sector under certain conditions may respond more strongly to an unexpected decline in the real price of oil than to an unexpected increase in the real price of oil of the same magnitude.[5]

The usual presumption in models of the transmission of oil price shocks is that the effects of lower oil prices on investment are the larger, the greater the decline in the real price of oil. The discussion in section 5, however, suggests that fixed investment by the domestic oil sector will decline disproportionately, once the expected real price of oil crosses a lower threshold. The reason is that oil investment depends not so much on the extent of the decline in the expected real price of oil, but on whether the real price of oil is expected to fall below the breakeven price, at which the cash flow of the investment is zero. In the latter case, domestic oil investment may cease rather abruptly. Thus, the relationship between the real price of oil and oil investment is inherently nonlinear. In practice, the threshold, beyond which oil investment stops, is likely to be smooth, given that different investment projects have different thresholds, but the economic intuition remains unchanged.

As long as the oil-producing sector in the domestic economy is quantitatively unimportant or the real price of oil is far from the threshold, this nonlinearity may be ignored for all practical purposes. The experience of the United States after June 2014, however, suggests that standard models of the transmission of oil price shocks to the U.S. economy may have to be adapted to account for this nonlinear behavior.

IMPLICATIONS FOR EUROPEAN OIL IMPORTERS

To the extent that European oil importers with the exception of Norway and the U.K. do not have an important domestic oil industry, one would expect the

5 This observation was first made by Edelstein and Kilian (2007) in the context of discussing the effects of the 1986 oil price decline on U.S. nonresidential investment.

decline in the Brent price of crude oil, all else equal, to have a larger stimulative effect on these economies than on the U.S. economy. There are several reasons why this stimulus may be smaller than one might have thought, however. First, one of the determinants of lower oil prices has been a slowdown in the global economy that is likely to slow growth in export-oriented European economies more than in the United States. Second, the Euro has been depreciating against the U.S. dollar after June 2014, offsetting in part the decline in the dollar price of Brent crude oil (see Baumeister and Kilian, 2016). Third, given the much larger share of gasoline taxes in European retail gasoline prices, the pass-through from lower oil import prices to retail gasoline prices is much smaller, and hence the response of consumers is more muted.

CONCLUDING REMARKS

Going forward, a question of obvious policy interest is whether higher investment in the U.S. oil sector will help offset the contractionary effect on private consumption of a future recovery of the real price of oil. As discussed in Baumeister and Kilian (2017), the answer to this question depends on how fast oil investment would grow in response to an increase in the real price of oil. This response will depend on the industry's expectations about the future evolution of the real price of oil and on the degree of uncertainty surrounding these expectations. How a recovery of the real price of oil would affect U.S. real GDP growth more generally also depends on the determinants of that recovery. Assuming that this recovery is of a similar magnitude as the cumulative oil price decline after June 2014 and composed of similar oil demand and oil supply shocks, all indications are that the response of the U.S. economy would be largely symmetric. For example, one would expect a negative stimulus from consumer and non-oil investment spending. Of course, as noted by Kilian (2009), no two oil price shocks are alike, and there is no reason to expect the composition, magnitude or evolution of the oil demand and oil supply shocks to mirror those in the past. For example, if a recovery of the real price of oil primarily reflected a more robust global economy, the overall effects on the U.S. economy would be less negative than if the oil price recovery were driven mainly by actual or anticipated oil supply shocks.

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