UNIVERSIDAD DE MÁLAGA

PH.D.THESIS

Doctoral Program in Mechanical Engineering and Energy Efficiency
Departamento de Máquinas y Motores Térmicos
Escuela de Ingenierías Industriales

TECHNO-ECONOMIC ASPECTS OF DISTRICT HEATING AND COOLING NETWORKS SUPPLIED BY COMBINED HEAT AND POWER TECHNOLOGIES

AUTHOR
JUAN PABLO JIMÉNEZ NAVARRO

SUPERVISOR
JOSÉ MANUEL CEJUDO LÓPEZ

Málaga, March 2019

AUTOR: Juan Pablo Jiménez Navarro

http://orcid.org/0000-0002-0309-4976

EDITA: Publicaciones y Divulgación Científica. Universidad de Málaga

"Fall in love with some activity, and do it! Nobody ever figures out what life is all about, and it doesn't matter. Explore the world. Nearly everything is really interesting if you go into it deeply enough. Work as hard and as much as you want to on the things you like to do the best. Don't think about what you want to be, but what you want to do. Keep up some kind of a minimum with other things so that society doesn't stop you from doing anything at all."

Richard Feynman

Resumen

La presente tesis se centra en el estudio del papel que las redes de distrito de calor y frío alimentadas por tecnologías de cogeneración tienen en el sistema energético. Las redes de distrito para el suministro de calor y frío facilitan la utilización de múltiples fuentes de energía y de tecnologías de generación que pueden posibilitar la reducción de emisiones de gases de efecto invernadero asociadas no solo al sector térmico, que incluye el suministro de calefacción y refrigeración, sino también al sector eléctrico.

Las redes de distrito constituyen un elemento importante para lograr la integración de los sectores eléctrico y térmico (sector coupling) y son actualmente reconocidas como un elemento fundamental en el futuro del sistema energético. En este sentido, la integración de dichos sectores térmico y eléctrico facilita la utilización efectiva de la generación de energía procedente de fuentes renovables, el incremento de la eficiencia del sistema energético en su conjunto y la reducción de emisiones de CO2.

Sin embargo, debido a la complejidad que supone el despliegue y operación de una red térmica de distrito, (incluyendo aspectos técnicos, económicos, políticos y sociales) la utilización de nuevos métodos es necesaria para facilitar la toma de decisiones a la hora de promover la utilización de dichas soluciones. Estos métodos son especialmente necesarios en países del sur de Europa donde la penetración de redes térmicas de distrito es limitada. De forma contraria a lo que sucede en el sur de Europa, las redes de distrito tienen una larga tradición en países del norte de Europa en donde las altas demandas de calefacción facilitan la viabilidad de las mismas. La existencia de estas redes hace que dichos países gocen de una posición de ventaja de cara a afrontar los futuros desafíos del sistema energético. No obstante, este hecho no debe hacer pensar que el éxito de las redes de distrito está exclusivamente vinculado a condiciones climáticas. Al contrario, casos de éxito demuestran que con un adecuado diseño de proyectos, las redes térmicas de distrito pueden ser viables independientemente de las condiciones climáticas.

Por ello, esta tesis propone modelos y métodos que pueden facilitar la penetración de redes térmicas de distrito en combinación con tecnologías de cogeneración. En concreto, este trabajo se centra en el análisis de redes térmicas de distrito bajo patrones de uso de energía típicos de países meridionales. El análisis propuesto incluye aspectos técnicos, económicos y políticos. Así, los métodos y resultados incluidos en esta tesis pretenden ser relevantes para legisladores, re-

sponsables de planificación energética e inversores energéticos. La presente tesis trate de dar respuesta a las siguientes cuestiones:

¿Cuáles son los métodos y modelos necesarios para facilitar la penetración de redes térmicas de distrito alimentadas por tecnologías de cogeneración en el sur de Europa?

A partir de esta cuestión principal, se pretende responder a las siguientes cuestiones específicas:

1. ¿Cuál es el estado del arte de las redes térmicas de calor y frío en lo que a diferentes enfoques de modelización se refiere?

Para responder a esta pregunta, esta tesis presenta un resumen de trabajos relevantes en los que se evalúan distintas técnicas de modelado y análisis de las redes térmicas de calefacción y refrigeración bajo distintos enfoques. Dado que los métodos presentados en esta tesis se basan en técnicas de modelado energético, esta revisión es fundamental para garantizar la contribución de este trabajo al estado del arte. Para ello, se han analizado los diferentes enfoques seguidos en la reciente bibliografía científica.

2. ¿Cuáles son los elementos que se deben incluir en los modelos de redes térmicas de distrito para facilitar el proceso de toma de decisiones incluyendo la planificación, el dimensionado, la priorización de inversiones y la operación de las mismas en el medio y largo plazo?

El objetivo de este trabajo es desarrollar un modelo marco que facilite la toma de decisiones en lo relativo a la planificación, dimensionado, inversiones y operación de redes térmicas de calor y frío en el medio y largo plazo. Este modelo marco se centra en aplicaciones que incluyen demandas tanto de calefacción como de refrigeración. El modelo propuesto se centra en aplicaciones urbanas que están por ser desarrolladas. En estas aplicaciones la implementación de redes resulta más efectiva desde un punto de vista económico y en las que los nuevos edificios a construir pueden ser diseñados de forma que se facilite su conexión a la red de distrito diseñada.

3. ¿Cuál es el papel de las tarifas reguladas (feed-in-tariffs) en la viabilidad de los sistemas de cogeneración que suministran energía a través de redes térmicas de distrito?

Esta cuestión pretende dar respuesta a la necesidad de diseñar adecuados mecanismos de apoyo a través de tarifas reguladas que garanticen la viabilidad de las redes térmicas de distrito y por tanto constituyan inversiones atractivas para el sector privado. Estas tarifas pueden ser fundamentales para garantizar la viabilidad de redes de distrito. Sin embargo, un mal diseño de las mismas puede dar lugar a insostenibilidades en el sistema energético desde un punto de vista económico. Así, el método propuesto proporciona el dimensionado óptimo de sistemas de generación bajo diferentes esquemas de tarifa regulada — diferentes niveles de remuneración para la energía eléctrica autogenerada. De esta forma, tanto reguladores energéticos como inversores pueden utilizar el método propuesto para comprender las implicaciones tanto del precio de la energía generada y remunerada bajo una tarifa regulada como del dimensionado y operación óptimos de la propia red térmica de distrito. Asimismo, el método propuesto pretende facilitar el establecimiento de colaboraciones público-privadas necesarias para explotar el potencial de las redes térmica de distrito para el suministro de las necesidades de calefacción y refrigeración.

4. ¿Cuál es el impacto del aprovechamiento del calor residual disponible en plantas térmicas en combinación con tecnologías de almacenamiento térmico en la eficiencia y costes del sistema eléctrico?

Esta última cuestión se plantea en un contexto de grandes cuotas de generación renovable en el sector eléctrico, fundamentalmente procedente de la energía solar fotovoltaica y eólica tal y como se prevé en los próximos años. Esta tendencia está provocando la necesidad de integrar los sectores térmicos y eléctricos (sector coupling) para lograr una mayor flexibilidad en el sistema energético. La integración de estos dos sectores permite la utilización de más fuentes de energía, como calor residual procedente de procesos industriales, y tecnologías de generación más eficientes que facilitarán la incorporación de una mayor generación de energía de origen renovable. En este sentido, el sector de calefacción — responsable del 50% de la energía final consumida en Europa — ofrece una gran oportunidad para integrar los sectores térmicos y eléctricos. Esta oportunidad ha sido reflejada en la Estrategia Europea de Calefacción y Refrigeración. En este sentido, este trabajo propone un modelo para la evaluación de la conversión de turbinas de gas, que actualmente operan en ciclos combinados, en turbinas operando en modo de cogeneración. El modelo propuesto también incluye la posibilidad de evaluar el impacto que las tecnologías de almacenamiento térmico de gran escala conectadas a una red térmica pueden tener en la operación de las centrales de cogeneración. Además permita evaluar el impacto de estas soluciones en el sistema eléctrico, incluyendo el efecto en la integración de más fuentes de energía de origen renovable. Por último, el modelo propuesto permita evaluar las ventajas derivadas de la utilización de las nuevas generaciones de redes de distrito (4ª generación) caracterizadas por unas menores temperaturas de operación, en la utilización de este tipo de plantas en modo de cogeneración. La integración de este modelo de plantas de cogeneración en otro de despacho energético permite la evaluación de costes no solo en el sector térmico sino también en el eléctrico, el impacto de la integración de ambos y el papel de las tecnologías de almacenamiento térmico de gran escala. Los casos de estudio presentados como respuesta a las cuestiones propuestas, además de validar los métodos propuestos, pretenden apoyar la idoneidad en la utilización de redes de distrito junto con tecnologías de cogeneración y como éstas pueden jugar un papel importante en el futuro del sistema energético incluso en áreas con inviernos suaves y veranos cálidos, típicos en el sur de Europa.

Estructura de la tesis

El presente trabajo se ha elaborado bajo el formato de compendio de publicaciones que han sido publicadas en revistas científicas de impacto. Las versiones originales de los artículos se incluyen como anexo en el presente documento. La tesis se ha organizado en los siguientes capítulos:

1. El capítulo 1 presenta el objetivo y alcance del presente trabajo tal y como se ha descrito anteriormente.

2. El capítulo 2 explica la importancia de las redes térmicas de calor y frío en el futuro sistema energético. Para responder a las cuestiones propuestas que han sido presentadas anteriormente, es necesario comprender el funcionamiento de estas soluciones y los potenciales beneficios derivados de las mismas.

3. El capítulo 3 analiza las tendencias relativas al modelado de redes térmicas de distrito a través de una revisión bibliográfica. Una exhaustiva revisión bibliográfica ha permitido garantizar que el presente trabajo constituye una contribución al estado del arte.

4. El capítulo 4 introduce los resultados obtenidos en los diferentes artículos científicos. Además, se incluye una discusión de los mismos.

5. El capítulo 5 concluye la presente tesis. A partir de los resultados obtenidos en el capítulo anterior, se extraen conclusiones y recomendaciones para futuras investigaciones.

6. Por último, las publicaciones científicas originales se incluyen en el anexo I del documento.

Lógica de los artículos científicos

Los artículos científicos propuestos evalúan la viabilidad de las redes de distribución de calor y frío. Cada uno de ellos analiza dicha viabilidad desde tres puntos de vista: i) análisis de coste-beneficio en el largo plazo, ii) modelo de negocio público-privado basados en tarifas reguladas de energía, y iii) utilización de fuentes de calor disponibles en plantas de generación térmica que puedan suministrar energía a través de redes de distrito, contribuyendo a la integración de los sectores térmicos y eléctrico. Por tanto, los tres artículos propuestos pueden ser considerados como un compendio de métodos complementarios que contribuyen al desarrollo de redes térmicas de una forma eficiente desde un punto de vista técnico y económico, apoyando la toma de decisiones en lo relativo al planeamiento energético y a las inversiones económicas asociadas. Los diferentes enfoques de los artículos científicos propuestos muestran la complejidad que implica la construcción, puesta en marcha y operación de una red de distrito. Además de esto, los artículos persiguen demostrar que las redes térmicas de distrito pueden operar bajo diferentes condiciones climáticas, incluidas aquellas típicas en países del sur de Europa.

Conclusiones y contribuciones

El presente trabajo se plantea con los objetivos de explorar oportunidades y desafíos que las soluciones energéticas a nivel de distrito deben afrontan para conseguir por un lado un suministro de energía más eficiente y por otro una mayor integración de la generación energética de origen renovable. El objetivo último del despliegue de redes de distrito es la descabonización del sector térmico, más aún si se tiene en cuenta que solo las necesidades de calefacción representan aproximadamente la mitad de la energía final consumida en Europa. La investigación llevada a cabo proporciona a los inversores y legisladores en materia de energía herramientas y métodos que facilitan la evaluación de dichas inversiones y la puesta en marcha de medidas de apoyo que posibiliten el despliegue de redes térmicas de distrito. La mayor motivación de este trabajo es la contribución a la penetración de redes térmicas de distrito en países del sur de Europa donde, al contrario que en países del norte de Europa, estas instalaciones no han sido ampliamente desarrolladas a pesar de su potencial en numerosas aplicaciones. Los resultados científicos presentados prueban que con el adecuado apoyo político y una selección adecuada de las opciones de generación en aplicaciones donde existe una alta demanda de energía, típica en áreas urbanas, el despliegue de redes de distrito puede permitir disfrutar de los beneficios derivadas de las producción combinada de electricidad y calor (cogeneración), permitiendo en concreto:

1. incrementar la eficiencia de los sistemas energéticos (térmico y eléctrico).

2. una mayor flexibilidad en el sistema energético, que ha sido a su vez reconocido como un factor clave a la hora de integrar mayores cuotas de energías renovables. En este sentido, la investigación también evalúa el papel del almacenamiento térmico en la integración de ambos sectores. Concretamente, las mayores motivaciones que han propiciado el desarrollo de la presente tesis han sido:

1. La implementación de un marco de simulación que permita una evaluación exhaustiva de la adecuación de redes térmicas de distrito en áreas urbanas no consolidadas pero con una proyección de alta demanda energética.

2. El desarrollo de un método para implementar políticas energéticas de apoyo a este tipo de instalaciones adaptadas a cada proyecto específico. A través de la utilización del modelo propuesto, estas medidas, en concreto la tarifa de venta de energía regulada, serán diseñadas de manera óptima garantizando tanto la viabilidad de los proyectos como la sostenibilidad del sistema energético desde un punto de vista económico.

3. La evaluación del impacto de la integración de los sectores de calefacción y refrigeración con el sector eléctrico para cuantificar como esta integración puede permitir la incorporación de fuentes de generación renovable adicionales, tal y como se espera en los próximos años.

Los principales resultados y conclusiones derivados de esta tesis se presentan a continuación para los tres artículos científicos:

Viabilidad de una red de distrito

En este trabajo se destaca la importancia de considerar determinados aspectos que son relevantes a la hora de dimensionar una red de distrito y su posterior viabilidad. Entre otros la existencia de medidas políticas que garanticen ingresos por venta de energía eléctrica, tales como "feed-in-tariffs" o "feed-in-premium", el efecto de la incertidumbre y la evolución futura de la demanda de energía en el distrito bajo estudio y finalmente la necesidad de combinar diferentes perfiles de usuarios para garantizar curvas de demanda de energía más uniformes que permitan un dimensionado y operación de los equipos de generación más eficientes. No obstante, la inversión necesaria para la construcción de la red, 7,5 M€ para una red de cuatro kilómetros como la considerada en el caso de estudio, tiene un efecto negativo en los periodos de retorno de la inversión. Por tanto, una de las principales conclusiones de este estudio es la necesidad de establecer medidas de apoyo que favorezcan la colaboración público-privada que permitan la operación de este tipo de instalaciones al tiempo que se minimizan o comparten los riesgos asociados a la inversión de las mismas.

The effect of feed-in-tariff supporting schemes on the viability of a district heating and cooling production system

Los sistemas de cogeneración pueden satisfacer simultáneamente la demanda eléctrica y térmica de forma eficiente — rendimientos totales de hasta 90% — especialmente en áreas con alta demanda energética por unidad de superficie (típicamente en áreas urbanas).

Como resultado de las conclusiones obtenidas en el artículo anterior y teniendo en cuenta las grandes inversiones requeridas debido fundamentalmente al coste de la construcción de la red y el alto riesgo de las misma debido a la incertidumbre de la evolución de la demanda en el medio y largo plazo, en determinadas aplicaciones se hace necesaria la aplicación de medidas concretas que faciliten la penetración de este tipo de instalaciones a través de garantías por la venta de energía.

Sin embargo, la proliferación de instalaciones sujetas a medidas específicas, en concreto aquellas relativas a la venta de energía eléctrica a precios regulados, ha puesto en peligro la sostenibilidad del sistema energético, dando lugar a la terminación de dichas medidas. Este hecho ha puesto en riesgo entre otros la viabilidad de redes térmicas de distrito así como las instalaciones de cogeneración.

Para facilitar la toma de decisiones por parte del inversor energético, esta investigación presenta un método para optimizar el dimensionado de los equipos de cogeneración que proporcionen las necesidades de calefacción, refrigeración a través de redes de distrito así como la gestión óptima de la electricidad autogenerada. De esta forma el modelo proporciona el tamaño óptimo de los equipos de generación dependiendo de las políticas de apoyo existentes (tarifas reguladas).

Como se demuestra en el caso de estudio presentado, grandes unidades de cogeneración aún requieren de ciertas medidas de apoyo para lograr una mayor penetración en el mix de tecnologías de generación.

Sin embargo, debido a la limitación en las fuentes de financiación disponibles, es importante un adecuado diseño de esquemas de apoyo que garanticen el beneficio tanto de inversores como del resto de actores, incluyendo usuarios finales y entidades públicas. En este sentido, el método propuesto permite a los legisladores definir medidas de feed-in-tariff de manera efectiva. En este artículo, la evaluación de esquemas de apoyo en vigor para el caso de estudio seleccionado demuestra que estos estaban bien diseñados, es decir, que la remuneración obtenida por la electricidad generada proporcionaba rentabilidades adecuadas. Además, también se comprueba que los modelos de feed-in-tariffs mejoran tanto la eficiencia como los costes de generación promoviendo el uso de tecnologías de cogeneración en combinación con almacenamiento térmico.

No obstante, una adecuada definición de feed-in-tariffs depende de las características específicas de cada proyecto. En el caso de estudio presentado, el coeficiente de operación (COP — coefficient of performance) de las enfriadoras de absorción es el parámetro con mayor impacto en los resultados económicos, modificando los beneficios en más de 10 c€ por euro invertido e incremento unitario del coeficiente de operación. Por el contrario, en la caso de la producción de calefacción, un incremento en la eficiencia de la caldera tiene un impacto cuatro veces inferior al caso de la enfriadoras de absorción. Estos efectos están sujetos a los perfiles de demanda.

La demanda de energía juega un papel fundamental a la hora de lograr la viabilidad de redes térmicas de distrito como se ha demostrado en el caso de estudio. En primer lugar, en los casos donde los perfiles de demanda muestran una alta variabilidad en periodos de 24 horas, la única posibilidad viable para los sistemas de cogeneración es la cobertura de la demanda base. De esta forma pueden operar a través de un mayor aprovechamiento de la capacidad disponible y en rangos de eficiencia mayores. En segundo lugar, la incertidumbre en la evolución de la demanda puede hacer que las inversiones no se lleven a cabo, especialmente en el sector servicios (edificios de oficinas) asociados a actividades económicas donde la demanda puede variar dependiendo del número de empresas usuarias de dichos edificios. Por último, el caso de estudio propuesto demuestra que bajo determinadas inversiones y costes de operación, restricciones legales destinadas a asegurar determinados niveles de eficiencia puede tener el efecto contrario en la operación de estos sistemas de generación, como se demuestra en el caso del rendimiento eléctrico equivalente. El efecto del rendimiento de las máquinas de absorción requiere de una nueva definición del parámetro rendimiento eléctrico equivalente que en lugar de considerar el calor de entrada en las enfriadoras de absorción considere la producción útil de frío en el cálculo de la energía útil generada. De no ser así, la actual definición del rendimiento eléctrico equivalente fomente la utilización de máquinas de absorción de bajo rendimiento.

The joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system

En este artículo presentamos un nuevo método para evaluar el beneficio derivado de la conversión de las turbinas de vapor existentes en las plantas de ciclo combinado en plantas de cogeneración y el impacto de dicha conversión en los sectores térmicos y eléctricos. El método propuesto se basa en un modelo de despacho económico, que incluye una representación detallada del sistema térmico (calefacción), permitiendo la evaluación de diferentes escenarios tales como diferentes capacidades disponibles para un conjunto de tecnologías de generación, distintos costes de energía o diferentes regímenes de operación de las plantas de cogeneración. La capacidad del método propuesto para vincular la optimización del sistema energético (térmico y eléctrico) con la temperatura de generación fijada en las plantas de cogeneración es un valor añadido del modelo, que entre otros permite evaluar el calor disponible para diferentes usos así como los beneficios derivados de la utilización de la 4ª generación de redes de distrito para calefacción caracterizadas por bajas temperaturas de operación.

El método ha sido aplicado a un sistema energético pequeño, que ofrece la oportunidad de suministrar calor a partir de la conversión una planta existente operando bajo ciclo combinado en una planta de cogeneración produciendo calor además de electricidad.

Los resultados demuestran que la conversión en plantas de cogeneración permite un incremento en la eficiencia del sistema energético, que de otra forma alcanza valores de eficiencia máximos del 50%. Este efecto se debe fundamentalmente a las altas eficiencias globales logradas mediante la operación en modo cogeneración de hasta un 90% para determinados puntos de operación. Sin embargo, el despliegue de plantas de cogeneración, a pesar de mejorar el rendimiento del sistema energético, puede dificultar la utilización de generación de origen renovable (curtailment). El análisis presentado demuestra que este efecto puede ser mitigado mediante la incorporación de elementos que proporcionen flexibilidad, tales como tecnologías de almacenamiento térmico. No obstante, existe un equilibrio entre la integración simultánea de generación de origen renovable y la conversión de centrales térmica en plantas de cogeneración.

El análisis para diferentes costes de calefacción revela que las plantas de cogeneración pueden competir frente a costes de suministro de hasta 10 €/MWh. Sin embargo para este coste reducido, las ventajas derivadas del aprovechamiento de las plantas de cogeneración se reduce y por tanto el beneficio derivado de la utilización de tecnologías de almacenamiento térmico.

Desde el punto de vista de la operación de las plantas de cogeneración, bajas temperaturas de extracción en las turbinas de vapor dan lugar a mayores eficiencias y menores costes. Por tanto, cuanto menos es la temperatura requerida de suministro mayor es la eficiencia del sistema. Sin embargo, esta mayor eficiencia en las plantas de cogeneración da lugar a un incremento de la energía de origen renovable que no puede ser aprovechada. Así cuanto la temperatura de extracción se incrementa de 60 a 120 °C, la energía renovable no aprovechada incrementa en un 1% para escenarios con alta penetración de renovables.

Por tanto se puede concluir que la conversión de plantas térmicas en plantas de cogeneración en combinación con almacenamiento térmico da lugar a más altas eficiencias y a menores costes. Sin embargo, en escenarios de alta penetración de fuentes renovables, los beneficios derivados de las plantas de cogeneración limitan la integración de dichas fuentes renovables logrando no obstante una reducción de costes.

A continuación se muestran los principales resultados obtenidos para los tres artículos científicos presentados.

Resultados destacados

Viability of a district heating and cooling network — Un modelo dinámico detallado de redes de distrito y distintas alternativas de generación es implementado para la evaluación de la viabilidad de redes térmicas de distrito.

— Los altos costes de la red térmica, que representan un 75% del coste total del sistema, dan lugar a largos períodos de retorno para el caso de estudio considerado.

The effect of feed-in-tariff supporting schemes on the viability of a district heating and cooling production system

— Se propone un modelo para la dimensionado óptimo de proyectos de tri-generación bajo distintos precios en la tarifa regulada para la electricidad producida.

— Los proyectos de tri-generación de gran escala todavía requieren de apoyo dependiendo del caso de estudio.

— Las políticas de apoyo público deben ser diseñadas para cada proyecto de forma específica

The joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system

— Un modelo de plantas de cogeneración con temperaturas de extracción variables es presentado

— Resolución de un problema de optimización de generación de calor y electricidad mediante un modelo de despacho económico

— Las plantas de cogeneración incrementan la eficiencia del sistema energético y reducen sus costes

— Las tecnologías de almacenamiento térmico reducen la cantidad de energía de origen renovable que no puede ser aprovechada al mismo tiempo que incrementan la eficiencia del sistema

— Las plantas de cogeneración son más competitivas cuando proveen calefacción a temperaturas más bajas (redes térmicas de 4ª generación)

Limitaciones de la tesis

A la hora de investigar cualquier sistema energético, la caracterización de la demanda de energía a satisfacer es una tarea compleja. Dicha caracterización requiere de suposiciones relativas al comportamiento de los usuarios a los que se les ha de proveer de energía. Como resultado, predecir la demanda de energía real es complejo. En este trabajo, hemos caracterizado la demanda de energía desde un punto de vista determinista. A pesar de ello, las conclusiones obtenidas pueden se reforzadas con análisis estocásticos. Es esperado que este análisis estocástico permita evaluar la representatividad de los resultados obtenidos.

Recomendaciones para el diseño de políticas y aspectos prácticos

En términos de políticas y aplicación de las mismas en el futuro sistema energético, tres recomendaciones pueden hacerse basadas en los resultados obtenidos. En primer lugar, el despliegue de redes térmicas de distrito debe estudiarse en detalle a la hora de conectar demanda y generación desde plantas de generación. Un análisis geo espacial de la localización de plantas de generación que pueden operación en modo cogeneración así como la distancia de estas a áreas de alta demanda energética por unidad de superficies permitirá estimar el verdadero potencial de las redes de distrito suministradas por plantas de cogeneración de gran escala. Un análisis de este tipo a nivel europeo, puede constituir una información muy valiosa a la hora de definir políticas energéticas que contemplen el use de las fuentes de calor disponibles en plantas de generación de gran escala. Segundo, la necesidad de esquemas de apoyo, tales como las tarifas reguladas (feed-in-tariffs) deben ser re-evaluadas en las actuales políticas energéticas en vigor. El subsidio de determinadas soluciones energéticas ha demostrado no ser siempre beneficioso desde una perspectiva holística del sistema de energía. Sin embargo, de acuerdo a los resultados presentados en este trabajo, en lo que se refiere al despliegue de redes térmicas en el sur de Europa, esquemas de feed-in-tariffs pueden garantizar la viabilidad de estas soluciones en determinados casos. No obstante, estas tarifas reguladas deben desarrolladas específicamente para cada proyecto garantizando unos niveles de rentabilidad adecuados en cada caso. Por último la electrificación del sector de la calefacción está ganando atención en la escena política. El empleo de bombas de calor, capaces de proporcionar altas eficiencias, pueden contribuir a la descarbonización del sector de la calefacción. En este sentido, la evaluación combinada de dos estrategias para el sector de la calefacción, por un lado la utilización del calor producido en centrales térmicas operando en modo cogeneración y por otro la electrificación de la generación de calor a pequeña escala requieren de un análisis exhaustivo.

Recomendaciones para futuras áreas de investigación

Como futuras líneas de investigación y de acuerdo a la esperada evolución del sistema energético, múltiples opciones están disponibles para evaluar diferentes mixes tecnológicos a la hora de integrar opciones adicionales como bombas de calor o almacenamiento eléctrico. En concreto, tres líneas de investigación merecen ser investigadas en detalle:

1. El rol del almacenamiento eléctrico en el suministro de la demanda térmica y su competitividad frente al almacenamiento térmico. El almacenamiento eléctrico ha experimentado una gran reducción de costes en los últimos años. La viabilidad del almacenamiento eléctrico puede abrir nuevas oportunidades tales como el despliegue de bombas de calor de gran escala que aprovechen como energía de entrada la generación eléctrica de origen renovable. Sin embargo, la fiabilidad de los sistemas de almacenamiento eléctrico debe ser investigada en más detalle antes de implementar escenarios globales que contemplen el despliegue masivo de esta tecnología. En esta línea, se han llevado a cabo algunos trabajos preliminares y presentado en la 11th International Renewable Energy Storage Conference (IRES 2017) bajo el título "Optimal Home Battery Sizing and Dispatch in EU Countries Taking Into Account Battery Degradation and Self-Consumption Incentives".

2. La segunda línea de investigación propone el análisis de la operación de plantas térmicas en modo cogeneración en combinación con bombas de calor, denominadas "booster heat pumps". El objetivo de esta línea de investigación es la evaluación de como la utilización de dichas bombas de calor pueden favorecer una mayor utilización de fuentes de calor de baja temperaturas y como asimismo pueden ser operadas en combinación con las centrales térmicas maximizando la eficiencia y minimizando costes.

3. Por último, la tercera línea de investigación se centra en la definición de un indicador que determine la idoneidad de incorporar tecnología de almacenamiento térmico a un determinado sistema energético. El indicador propuesto, análogo al

indicador del coste nivelado de energía (levelised cost of energy) para tecnologías de generación, deberá facilitar el análisis de viabilidad de la incorporación de capacidad de almacenamiento térmico en distintas aplicaciones de distrito promoviendo su utilización a través de la evaluación de dicho indicador. La literatura consultada muestra que este enfoque solo ha sido aplicado para tecnologías de almacenamiento eléctrico.

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Nomenclature

CSP	Concentrated solar power
PV	Photovoltaics
EV	Electric vehicles
PLF	Partial load factor
PLR	Partial load ratio
CAPEX	Captial expenditures
DH	District heating
RES	Renewable energy sources
DHC	District heating and cooling
CCHP	Combined cooling, heat and power
CCGT	Combined cycle gas turbine
STP	Science and technology parks
NUC	Nuclear
ICE	Internal combustion engine
FiT	Feed-in-tariffs
SH	Space heating
SC	Space cooling
SO	Single objective

MO	Multi objective
MILP	Mixed integer linear programming
COP	Coefficient of performance

European countries:

AT	Austria
BE	Belgium
BG	Bulgaria
HR	Croatia
CY	Cyprus
CZ	Czech Republic
DK	Denmark
EE	Estonia
FI	Finland
FR	France
DE	Germany
EL	Greece
HU	Hungary
IE	Ireland
IT	Italy
LV	Latvia
LT	Lithuania
LU	Luxembourg
MT	Malta

NL	Netherlands
PL	Poland
PT	Portugal
RO	Romania
SK	Slovakia
SI	Slovenia
ES	Spain
SE	Sweden
UK	United kingdom

Chapter 1

Aim and scope

This thesis focuses on the potential role of district heating and cooling networks fed by combined heat and power technologies in the energy system. District heating and cooling solutions can unlock multiple energy options to decarbonise not only the heating and cooling sector but the power sector, too. They represent an energy solution to achieve the sector coupling that has been acknowledged as a key feature of the future energy system. In this regard, sector coupling allows and enhances the utilisation of larger amounts of renewable sources, the increase of the efficiency of the energy system, and the reduction of CO_2 emissions.

However, due to its inherent complexity, involving technical and economic aspects as well as political and social factors, new methods are required to facilitate the decision-making and promote the deployment of thermal networks. This is especially needed in southern European countries where the penetration of district heating and cooling networks remains limited. On the contrary, northern European countries have a long tradition in the deployment of thermal networks — usually heat driven networks — creating a strong position for future energy challenges. What is more, a common misconception is to link the success of thermal networks to specific climate conditions. On the contrary, successful examples demonstrate that adequate project design guarantees the success of thermal networks despite climatic conditions.

This thesis aims to provide models and methods that can be used to facilitate the penetration of thermal networks fed by combined heat and power technologies. We focus on Southern energy patterns and we consider technical, economic and policy aspects. The proposed methods and results are intended to be relevant to policymakers, energy planners and, energy investors.

Research questions

In this section we introduce the main research question and the four sub-questions defined for this thesis:

What are the methods and models needed to facilitate the penetration of thermal networks, fed by combined heat and power, in South Europe?

The sub-questions are formed as follows:

1. What is the state of the art of district heating and cooling networks and the current modelling approaches followed?

   The first research question aims to present a summary of relevant works that tackle the modelling and analysis of district heating and cooling networks, including different approaches. Since the methods presented in this thesis are based on energy modelling techniques, focus will be given to different approaches followed in current and past literature. (Chapter 3)

2. What is the modelling framework needed for the development of the decision-making process to plan, size, prioritise investments and the operation of district heating and cooling networks in the mid- and long-term?

   The aim of this work was to develop a modelling framework to facilitate the decision-making process regarding the planning, sizing, investment and operation of district heating and cooling networks in the mid-to-long term. This modelling framework focuses on applications with both heating and cooling needs. It is also intended for new urban areas, where the deployment of thermal networks can be done more efficiently from the urban planning phase reducing the cost of the network construction and enabling the design of buildings in the area according to the specific energy supply option. (Chapter 4, Section 4.1)

3. What is the role of feed-in-tariff supporting schemes on the viability of a district heating and cooling production system?

   With this research question we aim to provide a method to design appropriate energy policy support in the form of feed-in-tariffs schemes to guarantee the feasibility of district heating and cooling networks fed by combined heat and power technologies. Put in a different way, the method provides the optimal size of the energy equipment given a fixed feed-in-tariff scheme in place. Thus, both policymakers and energy investors can take advantage of the proposed method that can improve the understanding of the operation of thermal networks at district level, contributing to the establishment of public and private agreements needed to unlock the potential of district heating and cooling solutions. (Chapter 4, Section 4.2)

4. What is the joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system?

   This chapter was developed in the context of a growing share of energy generation from renewable sources within the power system. This trend is raising the need of sector coupling that enables the utilisation of a wider portfolio of energy technologies and thus accommodating a higher amount of intermittent renewables sources. In this regard, the heating sector — accounting for the 50% of the total final energy used in Europe and characterised by low efficiencies — represents a great opportunity to couple with the power sector. This opportunity is highlighted in the European Strategy on Heating and Cooling. In this part of the thesis the conversion of a combined cycle gas turbines (CCGT) into a CHP operation mode in combination with centralised thermal storage option are modelled providing both electricity and heating by the connection to a thermal network. Thus, the model allows the evaluation of the impact of these solutions on the power system, especially regarding the integration of high shares of renewables. The model approach also allows the evaluation of how the new generation of district heating systems contributes to the utilisation of these types of plants. The integration of the proposed model on a power system dispatch model permits the evaluation of the cost reduction brought by the heating and electricity coupling via CHP and thermal storage. (Chapter 4, Section 4.3)

The case studies presented as answer to the proposed research questions aim to support that, even with completely different energy demand profiles and requirements, district heating and cooling networks together with combined heat and power technologies can play an important role in the energy system even in areas with relatively warm winters and hot summers.

Structure of the thesis

The current work has been developed as a compendium of articles published in relevant scientific journals. The original versions of the scientific articles are included in section A of this document.

The thesis is organised in the following chapters:

1. Chapter 2 explains the importance of district heating and cooling networks in the future energy system. The chapter examines the framework and provides the evidence of thermal network solutions. In order to reply to the main research question set, we need to comprehend the nature of these solutions and the interest in deploying them.

2. Chapter 3 covers the main trends in literature. An exhaustive review was carried out in order to develop the scientific framework and ensure the contribution's position in the state of the art.

3. Chapter 4 introduces the results obtained from the scientific articles published and further discusses the interpretation of the results.

4. Chapter 5 concludes this doctoral thesis. The findings are brought together to draw conclusions. Moreover, contributions to both policy and practice, and recommendations for future research are discussed.

5. Scientific publications can be consulted in annex A of the document.

Chapter 2

Introduction

Policy background and shifting towards the concept of the smart energy system

The European Commission has defined ambitious energy targets to achieve the decarbonisation of the energy sector in Europe. For 2030 the following goals have been set [1]:

1. A 40% cut in greenhouse gas emissions compared to 1990 levels
2. At least a 32%[1] share of renewable energy consumption
3. At least a 27% energy savings compared with the business-as-usual scenario.

In order to accomplish these goals, a holistic integration of different sectors such as electricity, heating, cooling, buildings and transport has to be achieved, leading to the implementation of the Smart Energy Systems [2]. This shifting approach is an essential step in order to accommodate a growing renewable energy generation — especially wind and solar — and subsequent requirement for a more flexible demand, including demand reduction, demand response strategies and energy storage [3]. In addition to the sustainability of the future of the energy system, this transition will pave the way to promoting local energy investing that can create approximately 10 million jobs in the EU [4]. Thus, the future of the smart energy systems relies on the following elements: new conversion and storage

[1] Recently approved as a provisional agreement that has to be endorsed by the European Council and the European Parliament, raising the previous target by 5%

technologies and a flexible demand. Figure 1 depicts a layout of the future energy system in which fossil fuels are completely replaced by renewable energy sources and bioenergy. Storage solutions play a substantial role in the future energy system.

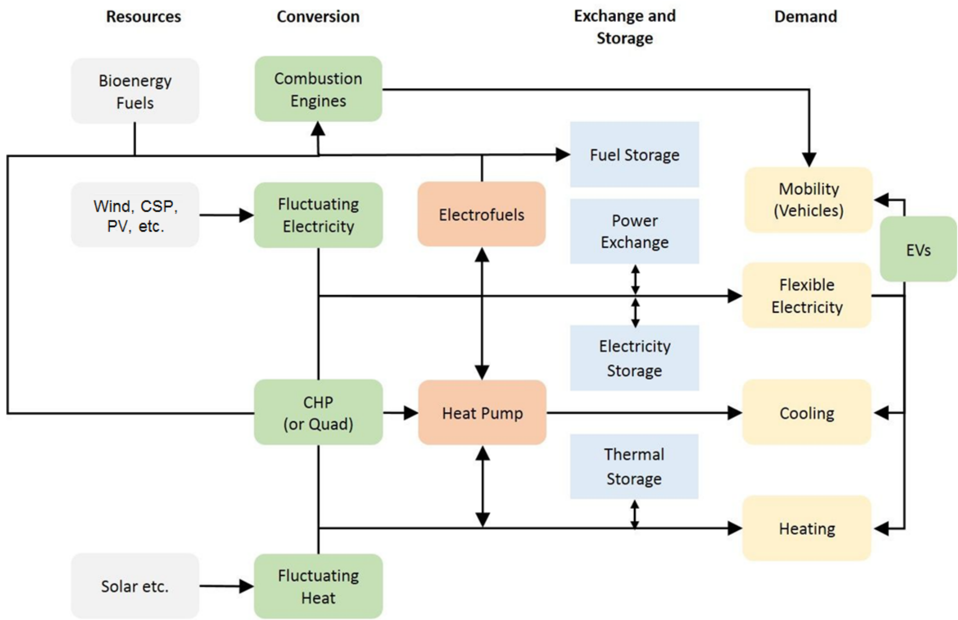

Figure 1: Future smart energy systems layout based on 100% renewable resources [5]

Advantages and disadvantages of thermal networks

Under this new paradigm, energy solutions at a district level have been highlighted as one of the most important key enabling approaches to make the energy transition possible.

District solutions aim to take advantage of the synergies between aggregated energy demands and centralised energy generation strategies in a cost-effective way. They could accommodate the aforementioned high shares of renewable generation [6], link centralised energy generation with the demand side increasing the efficiency of the energy system and, enable flexibility options via the deployment of centralised storage solutions. They embrace solutions such as micro-grids, storage options or thermal networks among others.

Concerning thermal networks, which deliver heat and cold, they could play a relevant role in the implementation of the Smart Energy Systems. Thermal networks allow the utilisation of unexploited energy sources such as waste heat deriving from industrial processes. They can enable higher-efficient centralised generation compared to decentralised options. Moreover, thermal networks can level the playing field to the development of flexible energy production strategies enabling the use of centralised thermal storage solutions — 10 times more cost-effective compared to electric storage [7].

In terms of energy efficiency improvements, thermal network solutions provide a more stable operation of the generation systems compared to decentralised systems, in which the frequency of start-ups and shut-downs is higher when supplying individual demands. Aggregated demands enable steady operation and thus limit low efficiency operation. Figure 2 shows the effect of a low capacity factor in the efficiency for a water-to-water heat pump with fixed capacity.

In addition to the efficiency improvement, large energy generation equipment reduces the marginal cost of the installed capacity. Thus, from an economic perspective, the CAPEX of a centralised solution is smaller for a given installed capacity (Figure 3).

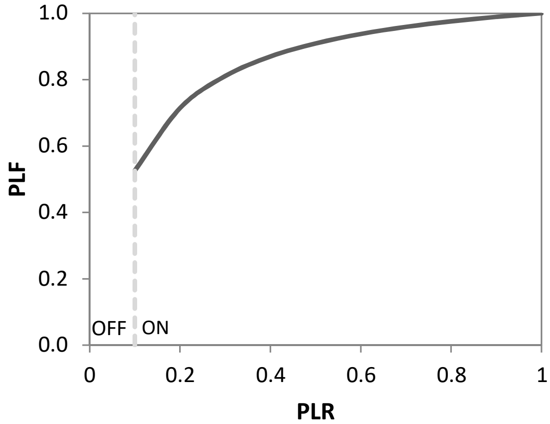

Figure 2: Partial load factor (PLF) as a function of the part load ratio (PLR), assuming fixed temperatures of operation [8]

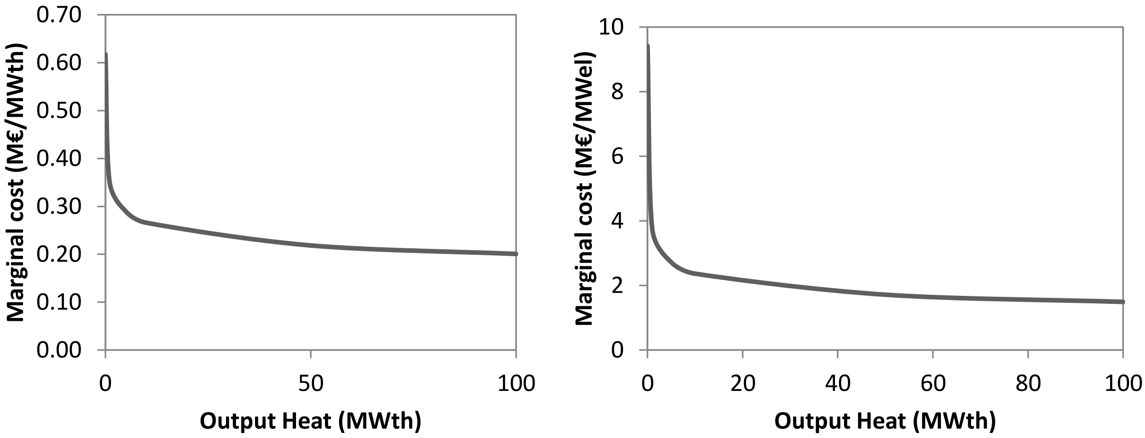

Figure 3: Marginal CAPEX cost of electric heat pumps (left) and natural gas fired turbines in combined cycle configuration (right) [9]

The downside of district heating and cooling networks is that they require an adequate and long-term energy planning strategy as they call for high upfront investments — especially those related to the construction of the network itself, more expensive than electric networks — and, lead to significant thermal transmission losses.

The high upfront investments costs and the characteristics of the energy demand, which are defined by the energy demand density and peak values among others, affect the economics of the thermal networks. Especially because the high dense populated areas are those that offer feasible opportunities for district heating and cooling networks [10]. However an adequate definition of the business case enlarges the adequacy of thermal networks beyond high energy dense areas. In this sense, recent research proves that feasible heat transmission can cover distances beyond 50 km for specific energy market conditions [11].

To provide readers with orders of magnitudes, following the method proposed by Persson and Werner in [12], and given a scenario defined by a building density of 0.4 sq-m of gross floor area per sq-m of land, and specific heat demand of 150 kWh per sq-m of gross floor area and year, the total piping cost is estimated at 8 M€.

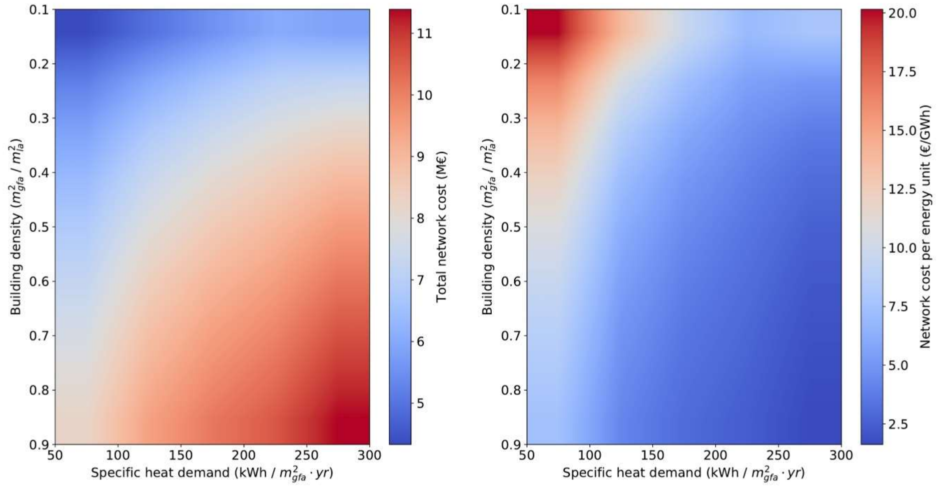

Figure 4: Thermal network investment cost for different building density and specific heating demand [9,12]

Concerning the long-term strategy and according to the literature review performed in this work, thermal networks can be under operation for 60 years [13]. To make the network investment profitable, given the associated high investment shown in Figure 4, the level of energy supplied should be guaranteed. Therefore specific business models have to be defined either by agreements with public administrations or by long term user engagement via attractive conditions. Nowadays, there are few examples in which the networks compete with conventional heat supply, as the case of the city of Barcelona, which also covers cooling needs, with a successful rate of end-user connections. In other cases, the public support is essential at least at the first stages of network deployment, before reaching the critical number of clients.

Regarding thermal transmission losses, many works have shown the benefit of decreasing supply temperatures not only because of the reduction of losses but also because it enables the utilisation of low quality energy sources [11, 14, 15].

In this regard, thermal networks have evolved from grids based on steam as heat carrier to low temperature (30 to 70 °C), grids using water as carrier. From the initial steam based networks, a temperature reduction has been pursued. Thus, the 2^{nd} generation of thermal networks used pressurised hot water over 100 °C, while the 3^{rd} generation operates with temperatures below 100 °C.

The new generation, 4^{th}, of district heating networks are operating with a decreased temperature of supply to the order of 30 to 70 °C minimising inefficiencies in the transmission of energy and also widening the range of supply options and demand requirements, leading to the concept of smart thermal grids that contribute to the implementation of the broader concept of smart energy systems [14, 16, 17].

Overview of district heating networks in Europe

Despite the potential advantages and opportunities that thermal networks bring into the future energy systems, their deployment varies significantly across Europe. In the case of district heating networks, their penetration ranges from countries with no district heating networks to others with a realised capacity of the order of 50% of the thermal demand, as the case of Denmark [18] (Figure 5).

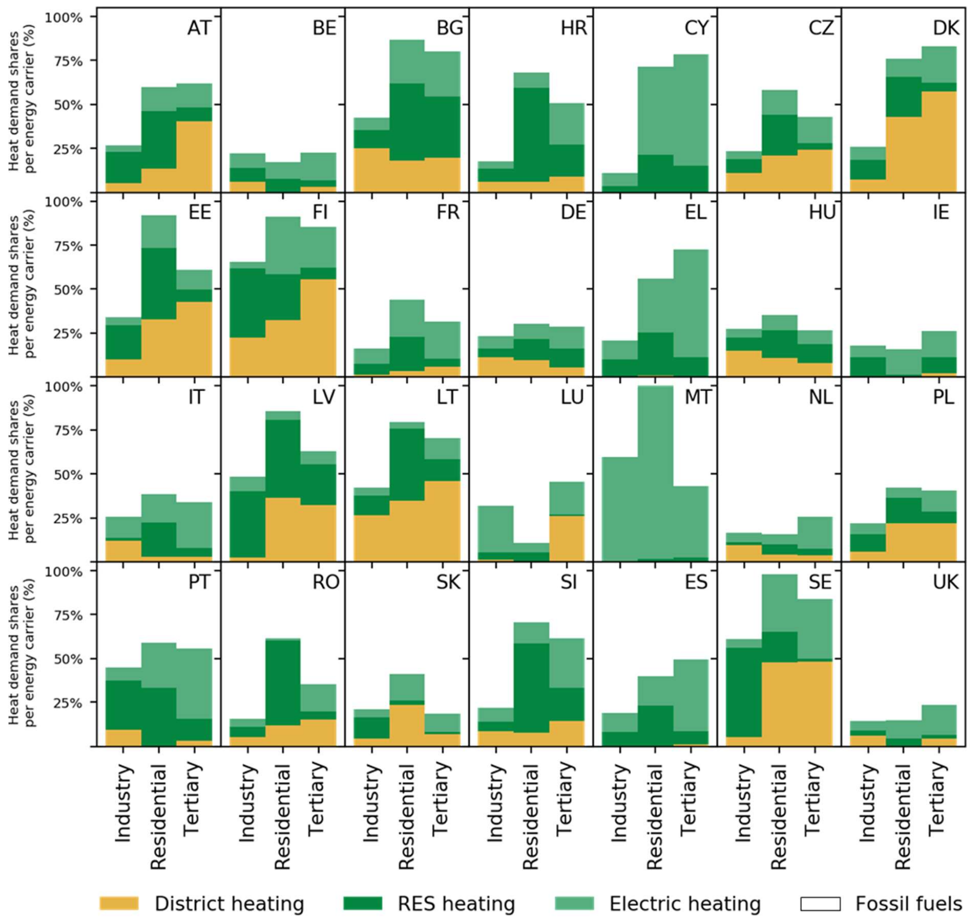

Figure 5: Share of heating demand provided by different energy carriers. 2015 [19]

As presented in Figure 5, countries with warm climate conditions do not show district heating deployment shares — CY, EL, MT and ES. On the contrary, northern countries like DK and FI present shares above 50% of the total heating supply in tertiary applications. It may be inferred that climate conditions determine the level of deployment of district heating and cooling networks. However, it has been demonstrated that climate conditions, despite playing an important role, are not decisive to the feasibility of district heating solutions [20]. As mentioned before, DHC enables the utilisation of multiple energy sources, even those with low quality from an exergy perspective — low temperature sources — within the new generation of district heating and cooling networks. In this regard, although the availability of energy sources may vary depending on the specific country conditions, the existing potential of heat sources is remarkable across Europe. Thus, for the specific case of Spain, which is one of the countries with a low level of DHC deployment, the annual industrial waste heat has been estimated of the order of 100 PJ [21], which roughly represents a 25% of the residential heat demand in the country, 2015 data, according to the profile described in [19].

Concerning cooling thermal networks, it is important to note that the size of cooling sector is 25 times smaller than the heating sector in terms of energy demand [19] and it represents a 1.25% of the total final energy demand in Europe in 2015, although it is expected to grow in the coming years [22]. Contrary to the heating sector, the cooling supply is mostly dominated by decentralised electricity-based technologies, because the portfolio of district cooling networks is limited (Figure 6). Sector wise, the tertiary is the largest, followed by the industrial and the residential (Figure 7).

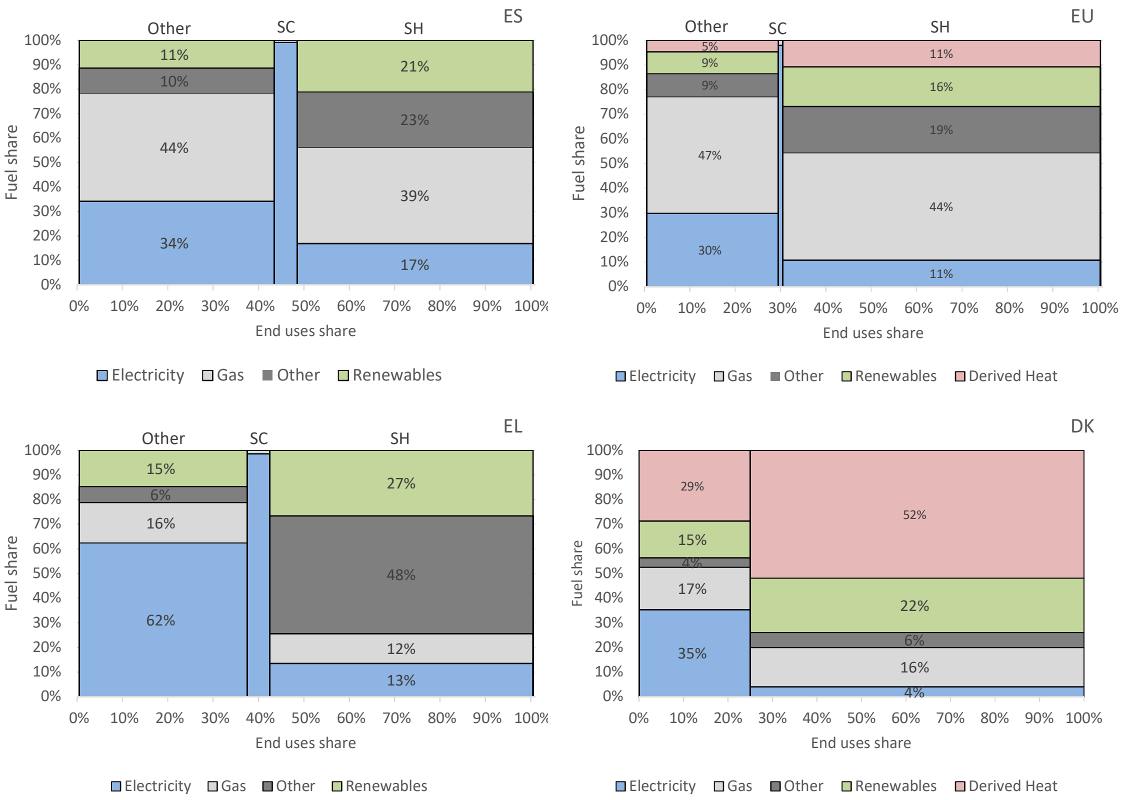

Figure 6: Overview on energy fuel and uses shares, including space heating (SH), space cooling (SC) and other uses [22]

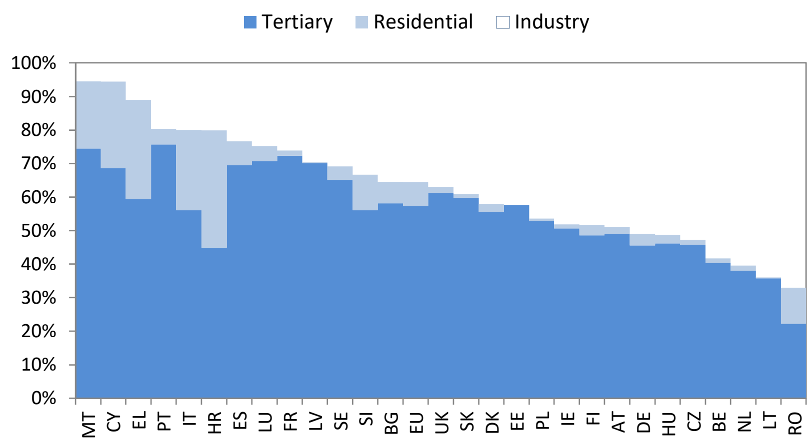

Figure 7: Share of cooling energy demand per sector [22]

Looking at the information available for a country like Spain, where cooling demand is supposed to have a more predominant role compared to other European countries, the deployment of cooling networks remains limited. Based on the latest (2017) available inventory data, in Spain there are approximately 350 thermal networks under operation that provide energy to around 4,400 building, with an aggregated length of more than 600 km and accounting for a total thermal installed capacity of 1.3 GW. Most of the existing networks only provide heat (91%), followed by those providing both heating and cooling (8%). Cooling networks only represent 1% of the total inventory [23]. In general, the European overview of the district heating and cooling networks deployment (DHC) suggests that despite being proven efficient, more efforts are required to unlock the potential of these energy solutions [18].

The major barriers that prevent from a larger deployment of thermal networks in those countries with lower penetration are:

- The low participation of the private sector in the ownership of thermal networks. In some countries like Spain, half of the registered thermal networks belong to public administrations.
- Lack of knowledge on the opportunities and options identified in the public entities responsible to promote these types of projects, mainly municipalities and local authorities.
- Uncertainty related to the level of energy demand to be supplied in the long term that may delay the payback of the high upfront investments.
- The need of long term contracts that may be perceived as a burden by public administrations due to the political time frame cycles.
- Unexpected risks derived from the construction, that increases the cost of the networks.
- Lack of urban planning, that makes difficult to deploy networks.
- In public-private partnerships, the impact of the public investment in the corresponding national, regional or local accounts – booked as debt, limiting the participation of public authorities.
- Last but not least, the perception of final users who, in many cases, are not in favour of sharing a common energy infrastructure, or do prefer to cover their needs with traditional means even if they miss potential energy savings, reduces the opportunities for this type of projects.

All in all, in order to realise the potential capacity, available energy sources, business models and energy market conditions including policy measures and user engagement have to be studied in detail.

Overview of combined heat and power technologies in Europe

Combined heat and power technologies (CHP henceforth) technologies have been widely acknowledged as instruments to produce important energy savings and CO_2 emission reductions compared with the individual production of heating and electricity. In addition, CHP technologies can also take advantage of renewable sources, such as geothermal or biogas, alternative fuels and waste heat. Fossil or renewable CHP technologies (waste and biomass) represent two thirds of the heat supply in all the European district heating networks for the period 1990 — 2014 [18]. However, its potential has not been fully realised due to aspects such as the difficulties to comply with electricity, heat and even cooling regulation, the lengthy permitting procedures or eventually high fees to start the operation for such types of plants [3]. Looking at the level of deployment of CHP at the European landscape, same trends as for the DHC case are found. Figure 8 depicts the share of installed capacity of four major energy technology generation groups and the expected evolution of shares until 2030 according to the EU reference scenarios [24]. Southern countries with extremely low penetration of district heating networks — CY, EL, MT and ES — , also show low levels of CHP deployment.

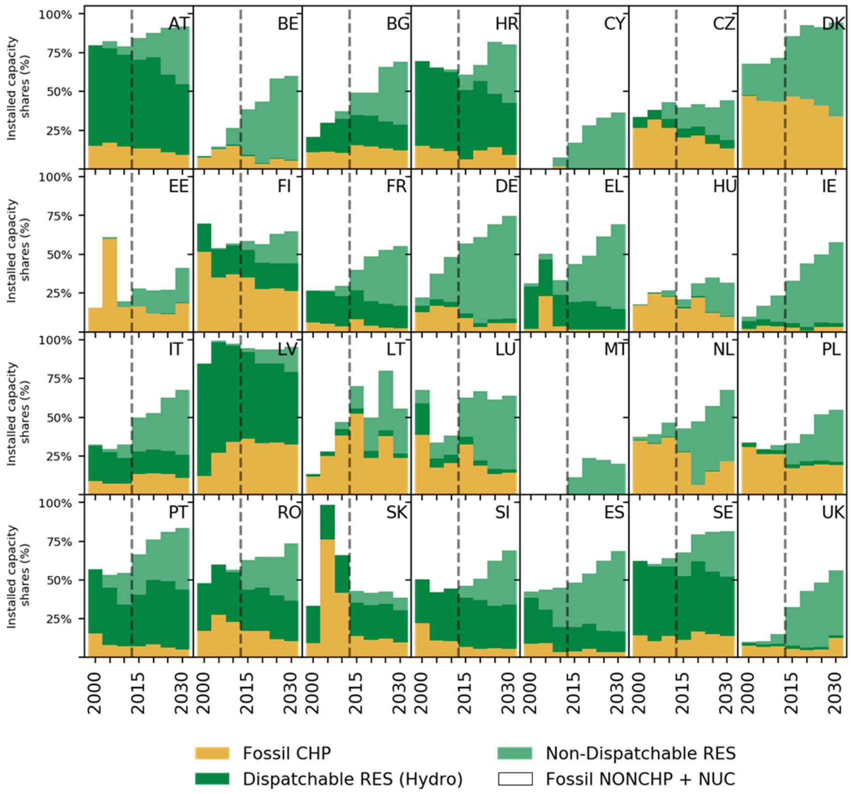

Figure 8: Share of installed net CHP generation capacity per year and Member State according to the EU reference scenario [25][2]

CHP technologies can significantly contribute to the realisation of future of Smart Energy Systems. Centralised CHP production connected to thermal networks links both electricity and thermal sectors by definition.

The importance of flexibility

In the last decade, renewable energy technologies — especially wind and solar — have undergone a sharp price reduction, leading to a greater reduction of the levelised costs of electricity compared with other conventional technologies [26]. This price reduction has resulted in high annual ratios of installed capacities. However, the intermittent nature of renewable energy sources requires the incorporation of technologies and methods that could bring flexibility, such as electric storage systems, into the energy sector, matching supply and demand at all times.

[2]Dotted line separates real historical data from projected values

Despite experiencing an extraordinary price reduction in the last five years [27], electricity storage has not been fully deployed due to economic and reliability aspects. In this sense, by using thermal storage to satisfy energy demand, the heating and cooling sector offers affordable flexibility options while maximising the utilisation of renewable sources via the utilisation of power-to-heat technologies.

Unlocking the coupling of heating and electricity sectors — Power-to-heat concept

As an additional effect, the deployment of the heating and cooling networks may unlock the potential of centralised heat pumps, allowing the conversion of renewable electricity into heat that could be directly used or stored at district level.

Combined heat and power technologies and fossil fuels

It is argued that fossil-fuelled CHP technologies do not contribute to the energy transition that pursues a fossil-free energy sector. However, they can contribute to the energy transition based on two different arguments in the short and medium-to-long term. In the short term CHP technologies increase the overall efficiency of the energy system and more importantly they contribute to the deployment of thermal networks unlocking the advantages presented before. In the long term, CHP technologies can undergo a fuel shift from fossils to biofuels when gas is due to be phased out [28].

Given the current energy sector status, we have considered that gas will be used in a mid-term horizon [29] and thus it is considered as the main energy sources in the studies described in this work. The methods and contributions presented in the following chapters will be still valid if natural gas is replaced by biogas, just by adjusting the economics for the new fuel.

Chapter 3

State of the art

District heating and cooling networks have been extensively studied in the last years from multiple approaches. Due to their complexity, variety of configurations, and uses, thermal networks could be evaluated under different dimensions including technical, economic, environmental, social and policy aspects [30]. The aim of this section is to present a summary of relevant works that tackle the modelling and analysis of district heating and cooling networks including those different approaches. As the methods presented in this thesis rely on energy modelling techniques, focus will be given to the different modelling approaches followed in previous scientific research. From a broad perspective, the literature review performed reveals that in most scientific works, analyses evolve around three major elements that form the district heating and cooling networks: i) the energy sources that feed the network, ii) the energy demand profiles, and iii) the model of the thermal network itself. The modelling of these three elements varies depending on the level of detail pursued in each case [31]. Different approaches for these three major elements are discussed below.

Energy resources

Due to the great amount of sources that district heating and cooling systems can accommodate, previous studies examine a large range of energy sources depending on the case study design in each analysis [30, 32]. Most common energy sources are: gas-based combined heat and power plants (CHP), renewable sources — including biomass [33–35], geothermal and heat pumps [36–40], solar energy [32] and industrial waste to energy [11, 41, 42]. Predominance of gas-based CHP technologies feeding thermal networks has been identified although heat pumps, including geothermal heat pumps [43–47], are gaining momentum endorsed by the foreseen future of the energy system that aims to phase out not only coal but also gas in the medium to long-term.

Energy demand profiles

This element is acknowledged as the most important input data when simulating and optimising energy systems [48]. Yet, different studies follow simplified approaches to calculate the energy needs based on metrics such as the Heating Degree Days (HDD) — defined as the number of degrees that a day's average temperature is below a reference temperate defined as the lowest daily mean air temperature not leading to indoor heating (typically 15 °C), the Cooling Degree Days (CDD) — defined as the number of degrees that a day's average temperature is above a reference temperate defined as the highest daily mean air temperature not leading to indoor cooling (typically 24 °C). Others use the Energy Use Intensity (EUI) defined as the energy demand per unit of surface or the load factor (LF) [49].

To capture the variation of thermal demand that affects the design of the network and the energy production and operation of units, detailed energy demand data, typically with an hourly level of resolution, are widely used. Among others, this approach leads to the utilisation of load duration curves that ultimately has been used to develop sizing methods for combined heat and power plants [50]. Beyond the timescale resolution, regarding the methods used to calculate the actual demand values for a given time step scale, it is common to find complex methods to calculate demand that include a large number of inputs parameters and solve heat balance equations with a high level of detail. In many cases, these approaches rely on detailed energy simulation tools such as Energy Plus [51] or TRNSYS [52]. However, they also account for associated high computation costs and uncertainties on the input data that feed those models. In intermediate approaches, some authors formulate and solve the state-space equations based on the electrical analogy of the thermal problem [53, 54]. In most of the works, these methods are applied to implement building models for residential and commercial uses. Despite enabling more detailed analysis, when the calculation of the hourly demand profile is followed by the resolution of the optimisation problem, some authors have proposed techniques to minimise the computational cost of the problem[55, 56]. In this line of research, identified works rely on clustering techniques that make it possible to select typical days while controlling the associated error [55, 56]. A proposed classification that covers a wide variety of methods to calculate energy demands with increasing complexity, is discussed in [31] and summarised in Table 1.

Table 1: Summary of modelling approaches to compute the energy needs to be satisfied by district heating and cooling networks [31]

Methods Approach	Method
Historical methods	Heating and cooling degree days Energy use intensity and Load Factor Direct measurements Archetype buildings
Deterministic methods	Complex models Simplified models
Predictive time series methods	Predictive models Artificial intelligence

The same study concludes that many of the analyses carried out rely on simplified methods (mainly based on the peak values) have proven to be suitable for sizing the thermal networks. However, these models fail when evaluating the dynamic performance of the district energy system network requiring more detailed analysis. In addition to the above, new methods can be found in recent publications that aim to facilitate the characterisation of the building energy needs at urban level. In this regard, statistical methods based on the urban building energy modelling (UBEM) tool have been used to characterise large building stocks [57]. In another study following the statistical approach, a method is proposed to build hourly demand time series based on cadastral data [58]. Regardless of the method selected, outputs are compared with real data available.

Energy distribution network

Regarding the modelling of the distribution networks, two main approaches are identified according to [31]; the stationary equilibrium and the dynamic models. The first approach is based on the combination of mass flow and energy balances while the latter group could be modelled via dynamic heat transfer equations or state-state equations depending on the temperature of operation of the network [59]. More specific studies have implemented analysis on the optimal operation of the networks [60]. Finally, another group of studies focuses on the geo spatial analysis of the thermal network seeking to identify the optimal spatial development of thermal networks [61, 62].

Modelling approaches

From a holistic approach, which tackles the integrated analysis of the previously presented elements, modelling approaches fall into two main groups: heuristic and optimisation modelling. In the latter, models are designed to evaluate the effect of different parameters in the performance of the energy system. while in the latter, the models calculates the combination of input parameters values that optimise (minimise or maximise) a certain feature of the system such as maximum revenue, energy production or renewable integration, minimum emission, operation costs, or investments [63]. On the other hand, depending on whether models consider uncertainty; deterministic and stochastic models are also identified [32].

Based on the variability of modelling approaches, there are available software tools to model thermal networks, including production, distribution and consumption that pursue different goals. Table 2 presents a list of tools and their applications.

Table 2: Available software tool to simulate district heating systems [32]

Software	Developer	Application
EnergyPlan	Aalborg University, EMD A/S and PlanEnergi	Optimization of energy, environment and economic impact of energy systems
energyPro	EMD International	Modelling package for cogeneration and tri-generation plants of fossil fuels, biomass and other complex energy systems
Homer	National Renewable Energy Agency in USA	Simulation and optimization of stand-alone and grid connected energy resources
LEAP	Community of Energy, Environment and Development	Energy policy application and climate change analysis
MiniCam	Pacific Northwest National Laboratory	Long-term and large-scale changes in global and local energy systems
MODEST	Optensys Energianalys	Cost optimization of energy production
Nems	EIA	Energy/economic/environment of U. S. energy market
NetSim	Vitec	Grid simulation software for district heating/cooling
PRIMES	National Technical University of Athens	Energy supply and demand simulation
RAMSES	Danish Energy Agency	Simulation of electricity and district heat
RetScreen	Natural Resources of Canada	Evaluating energy production, life cycle cost and greenhouse gas emissions of renewable energy sources
SimREN	Institute of Sustainable Solutions and Innovations	Modelling of energy supply and demand
TERMIS	Schneider Electric	Real time planning and optimization of DHS distribution
TRNSYS	University of Wisconsin	Simulation of transient energy systems

The first peer-reviewed paper included in this thesis, entitled "Viability of a district heating and cooling network" (section 4.1) is developed using TRNSYS to model the thermal network. It gives emphasis to the assessment of the opportunities that thermal networks may bring via the implementation of a detailed model. Thus, this work offers a solid framework to evaluate the dual heating and cooling business model.

Optimisation approaches

Studies that evaluate optimal solutions of district energy systems could be classified depending on the optimisation formulation and scope into: the distribution network, the superstructures, the operation and planning and the subsystems building blocks and their interaction with the network [63]. As presented in Table 3, optimisation approaches include technical, economic and environmental aspects as elements of the objective function. When multi-objective functions are considered in many cases a weighted-sum function is computed [63]. The formulation of the different studies includes linear, non-linear and mixed-integer linear programming. However, it is common to use constant efficiencies to avoid non-linear formulations [64–66]. The second contribution to this thesis, entitled "The effect of feed-in-tariff supporting schemes on the viability of a district heating and cooling production system" (section 4.2) falls into the category of superstructures solving a mix-integer linear programme. However, contrary to the objectives identified in the majority of approaches, this optimisation aims to assess supporting schemes — feed-in-tariffs schemes trigger the optimal size and operation of combined heat and power plants.

Table 3: Summary of optimisation approaches [63]

Approach	Opt type	Method/ Algorithm	Objective(s)	DH type	Solver
	SO	MILP	Total annualized cost of micro-grid	Centralized	GAMS CPLEX
	MO	MILP	Both economic and environmental aspects	Decentralized	Not mentioned
Super structures	SO/MO	MILP	Annual cost and carbon dioxide emission	Decentralized	MATLAB/ Gurobi
	SO	MILP	Selection of new users	Centralized	Opti-TLR CPLEX
	SO	MILP	Costs savings and reduction in CO_2 emissions	Decentralized	CPLEX
	SO	NLP	Sum of annual variable costs	Centralized	AIMMS/ W-ECoMP
	SO	MILP	Annual investment, operating and maintenance costs	Combined	Xpress
	SO	MILP	Cost-efficient heating network	Centralized	Xpress

Approach	Opt type	Method/ Algorithm	Objective(s)	DH type	Solver
Operation and planning	SO	MILP	Operating costs for heat production	Centralised	CPLEX
	SO	LP	Costs of the net acquisition for heat power in deregulated power market	Centralised	LP2
	SO	MILP	Dispatching strategy for the different power sources	Centralised	MATLAB
	SO	Newton method	Total mass flow rate / total thermal conductance	Centralised	Not mentioned
	SO	MINLP/MILP	Capital and operating costs	Centralised	CPLEX
	SO	MILP/MINP	Annual CAPEX, O&M cost of CCHP	Centralised	GAMS CPLEX
	SO	MILP/MINLP	System operating costs (fuel and grid)	Centralised	MATLAB/BONMIN
	SO	NLP	Pumping cost and heat loss cost	Centralised	MATLAB
	SO	GSO	Energy consumption	Centralised	MATLAB
	SO	MILP	CO_2 emission and running cost	Centralised	Not mentioned
	SO	Genetic Algorithm	Sum of fuel and pumping cost	Centralised	MATLAB/C++
	SO	MILP	Overall operation costs	Centralised systems integration	CPLEX

Approach	Opt type	Method/ Algorithm	Objective(s)	DH type	Solver
	SO	NLP	cost per unit of thermal energy used	Centralised	Not mentioned
	SO	LP	overall net; acquisition cost for energy	Centralised	LP2; EnergyPro
Distributed integration	SO	MILP	profit of CHP plant by selling electricity	Centralized	GAMS CPLEX
	MO	Kruskal & Genetic algorithms	costs of power & heat supply & CO_2 emission equivalents	Decentralized	Not mentioned
	MO	Kruskal & Genetic algorithms	costs of power & heat supply & CO_2 emission equivalents	Decentralized	Not mentioned
	SO	MILP	Total annual costs including investment and operating	Centralized	GAMS CPLEX
	MO	NLP	total exergetic efficiency and total net power	Decentralized	MATLAB
	SO	Hybrid optimization	Total net present cost	Centralized	HOMER

Approach	Opt type	Method/ Algorithm	Objective(s)	DH type	Solver
Subsystem building blocks	SO	Calculus-based	Pipe investment costs	Centralised & Decentralised	Not used
	SO	Genetic Algorithm	Calibration	Centralized	MATLAB
	SO	Genetic Algorithm	Annual variable cost	Centralized	W-ECoMP
	SO	Genetic Algorithm	investment, depreciation, maintenance, heat loss, and operational cost of circulating pumps	Centralized	Not mentioned
	SO	control vector parametrization (CVP) algorithm	Operation cost	Centralized & Decentralised	gPROMS gOPT
	SO	Genetic algorithm	Annualized price of distribution network	Centralized	Not mentioned

Integration of the heating and the power systems

As highlighted in the introduction, energy sector coupling is gaining momentum as a way to decarbonise the energy sector by increasing the flexibility of the coupled systems, and thus facilitating the penetration of renewable sources [67]. Accordingly, research works are approaching energy sector coupling focusing on the production of combined heat and power. Many of the works that have been analysed in this study consider a set of centralised CHP units and discuss about different modelling approaches to solve the combined operation of the CHP and the power systems. In the literature review, studies that focus on the minimisation of the cost of the power system have been identified. In doing so, authors have worked on the validation of different mathematical approaches [68–71]. Another group of studies focuses on the advantages derived from the integration of both sectors disregarding the effect on the power system operation. This approach includes not only CHP technologies but also heat pumps and renewable energy [44, 72, 73]. Other authors stress the importance of shifting the current smart grids toward the concept of smart energy systems with the aims of incorporating more renewable sources and linking electricity and heat sectors [74]. However, none of the indicated studies tackle the quality of the heat provided and therefore its ability to meet the energy requirements. Regarding the role of storage technologies under this new paradigm and together with the analyses of sector coupling, storage options are more frequently included in the analysis, with thermal storage being predominant compared to electric storage, even though the latter is drawing attention due to its extraordinary price reduction [75–77]. Within this context, the third peer-reviewed article included in this thesis and entitled "The joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system" (section 4.3) provides a method that determines the optimal dispatch of a combined power plant, the quality of the heat provided in terms of temperature and how this temperature can support the 4th generation of district heating and a better operation of the CHP plants.

Energy policy support

Finally, the last subject tackled in this thesis covers the work done for evaluating measures that enhance the opportunities of district heating and cooling networks. In this matter, previous studies focus on renewable technologies, mostly solar and wind that have traditionally been the beneficiaries of financial supporting schemes — feed-in-tariff and feed-in-premium support. Few examples are identified that assess the impact of those measures in either thermal networks or combined heat and power plants. In more detail, some analyses focus on the competitiveness of district thermal networks compared with conventional gas networks [78]. Others explore the policy measures possibilities to facilitate the upgrade of district heating networks [79]. Lastly, other analyses evaluate the optimal feed-in-tariff support for a given energy generation system [80]. Under this dimension, the contribution to this thesis entitled "The effect of feed-in-tariff supporting schemes on the viability of a district heating and cooling production system" (section 4.2) aims to provide a method to design and size appropriate feed-in-tariff scheme that in one hand attract the interest of investors while in the other do not compromise the long-term feasibility of the energy system, ultimately affecting the price of the energy for final users.

Contribution of thesis

Many studies focus on separate modelling approaches of the different elements required to carry out a comprehensive evaluation of thermal networks namely: heat demand, energy generation technologies and thermal network themselves. Moreover, few studies focus on the assessment of policy options that can contribute to the deployment of these energy solutions.

This thesis brings together different approaches followed in previous works in order to provide methods to support decision-making process when it comes to the deployment of thermal networks from a technical, economic and policy perspective. In other words, we provide a holistic approach to the research of district heating and cooling networks with the end goal of proposing policy recommendations for their deployment in South Europe.

The proposed methods, in this thesis, rely on detailed energy demand assessment and long-term energy planning. The dynamics of the energy demand are needed to carry out detailed evaluations. An hourly resolution demand, as used here, allows the accurate size of equipment and the assessment of thermal storage solutions. Yet, a trade-off between a high detailed energy demand and the computational cost of the optimisation resolution is pursued. Thus, clustering techniques are proposed. Regarding long-term evaluation, a method is proposed to assess how energy demand of new areas could evolve along years.

A sensitivity energy pricing method is proposed to set effective energy policies. The method, in this thesis, identifies the optimal energy tariff schemes to guarantee the feasibility of combined heat and power installations to meet energy needs via thermal networks.

Last, this thesis proposes an integrated detailed model of the coupling of the power and heating sector. It allows the evaluation of the temperature of operation in the network. Therefore, it supports the transition towards the new generation of thermal networks.

Chapter 4

Results and Discussion

This chapter presents the major results derived from the three peer-reviewed scientific articles included in this thesis. The original versions of the articles are included in the appendix A of the document. Thus, this chapter does not discuss in detail the methods and case studies described in the articles but rather focuses on the novelty of these works and their main findings and implications.

Rationale behind the set of papers

As explained in chapter 1, the three papers assess the viability of district heating networks. They approach the assessment of their viability from three different approaches; : i) long-term cost-benefit analysis, ii) public-private business case base on supporting schemes, and iii) the utilisation of the available heat in centralised power plants to supply district heating networks, under the sector coupling strategy. Therefore, they could be understood all-together as a compendium of complementary methods that can support the deployment of thermal networks in a cost effective way supporting the energy district planning and the investment decision-making process. Considering the complexity of the topic, one may think that other approaches would serve this purpose. However this multiple approach itself serves as an example of their complexity. In addition to the above, this work aims to demonstrate that thermal networks can be deployed under different climate conditions. Thus, the case studies presented in the three peer-reviewed papers focus on areas with warm winters and hot summers, which can be found in southern European countries.

4.1 Viability of a district heating and cooling network

Juan Pablo Jiménez Navarro, Rogelio Zubizarreta Jiménez, José Manuel Cejudo López
DYNA 87 (2012) 305 - 315

Author attribution

R. Zubizarreta and J.M. Cejudo designed the goals of the study; J.P. Jiménez-Navarro and R. Zubizarreta developed the methodology to characterize the demand and the implementation of the building models used in the study; J.P. Jiménez-Navarro and R. Zubizarreta designed and set up the energy generation models and the techno-economic assessment; J.P. Jiménez-Navarro performed the analysis; J.M. Cejudo validated the results of the study; J.P. Jiménez (with comments from the co-authors) wrote the manuscript.

Context

This work is developed in the framework of the project "Estudio de viabilidad de una red de distrito para el abastecimiento energético de la ampliación del Parque Tecnológico de Andalucía" — Viability of a district heating and cooling network to supply thermal energy demand in the Andalusian Science and Tech¬nology Park (STPs). The project consortium was composed by several research organisations including the University of Málaga and the Andalusian Institute of Technology. The project was funded by the Spanish Ministry of Economy and Competitiveness to foster the modernisation of these areas.

Scope

The aim of this work was is to develop a modelling framework to facilitate the decision-making process regarding the planning, sizing, investment and operation of district heating and cooling networks in the mid-to-long term. This modelling framework focuses on applications with both heating and cooling needs. It is also intended for new urban areas, where the deployment of thermal networks can be done more efficiently from the urban planning phase reducing the cost of the network construction and enabling the design of buildings in the area according to the specific energy supply option. The multi-annual approach of the study aims to determine the investment strategy over years based on the evolution of the heat demand of new areas. Thus, the model evaluates how the energy demand is evolving based on the rate of the occupation of new buildings. Therefore, the final goal of this work is to prevent from over-sizing the energy production systems that supply the district heating and cooling networks as a consequence of real levels of demands lower than expected in the design phase and thus leading the low capacity factors and low efficiencies. Although uncertainty is a major issue when facing new urban areas, this approach aims to identify the appropriate levels of demand required to invest in specific energy generation technologies based on a deterministic demand trend. Based on the long-term vision, this work offers a method to carry out a comprehensive assessment of the techno- economic viability of thermal networks, including a thermal demand forecast, the analysis of the performance of different energy generation technologies available, the size and dimension of the networks and the evaluation of the economic benefits derived from the operation of the network along a time frame — typically 20 years. The modelling framework is implemented by modelling the following elements: the characterisation of the energy demand, the modelling of the energy system and the techno-economic assessment.

Characterization of the energy demand

To characterise the energy demand, a sub-method has been developed based on two steps:

- i) The clustering of the existing building stock leading to the identification of building archetypes and the projection of future buildings to be incorporated in the area of expansion under study.
- ii) The clustering is then followed by the implementation of high detailed models of building archetypes implemented in Energy Plus [52] and validated by the available bibliography on building demand and combined with real data accessible for some of the buildings if available [81].

The incorporation of new building rate is based on the analysis of the building trends and associated economic activity in the area under study, leading to the definition of an annual new building settlement rate. Figure 10 shows the evolution of the additional building surface along the years; meanwhile figure 11 gives an example of a building archetype implemented.

Thus, following a bottom-up approach, buildings — defined by the useful sq-m surface — are incorporated along the coming years. Contrary to traditional cost-benefit analysis that relies on a typical year and then extrapolates the results for the installation lifetime, this work proposes a demand evolution that impacts the operation of thermal networks especially in the first years when new areas are not fully consolidated.

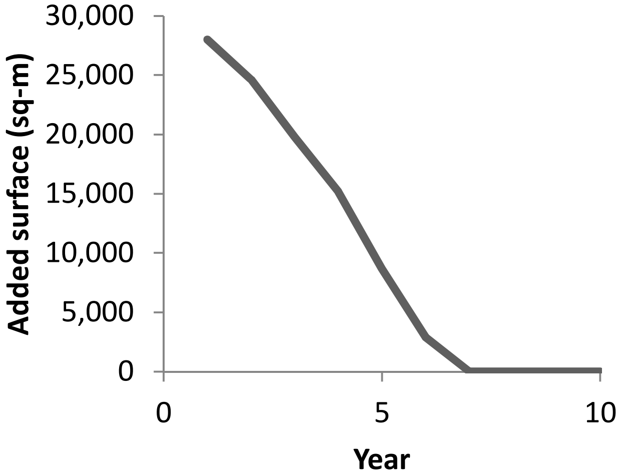

Figure 9: Forecast evolution of new buildings in the expansion area

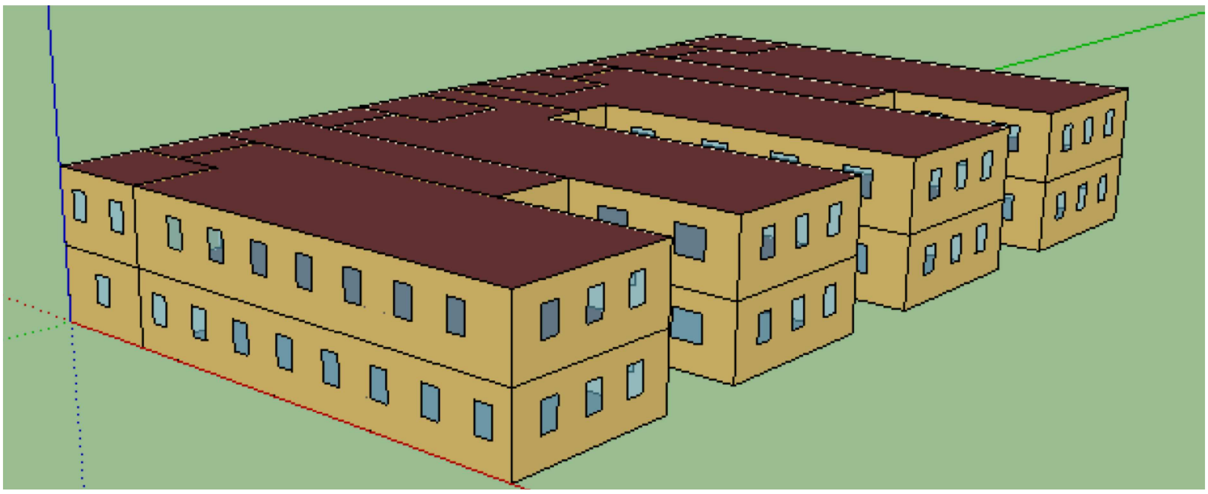

Figure 10: Example of the energy building model. Office building

Modelling of the energy system

The next step in the method is the evaluation of the different energy generation alternatives. To do so, a detailed modelling test-bed is designed and set up. The model allows the evaluation of different energy generation technologies. It also allows setting other aspects such as set-point tem¬peratures, size of the thermal networks or external conditions such as ambient or ground temperatures that can be tuned according to the case study. Thus, this modelling framework is suitable for many other case studies. The model is implemented in TRNSYS [52].

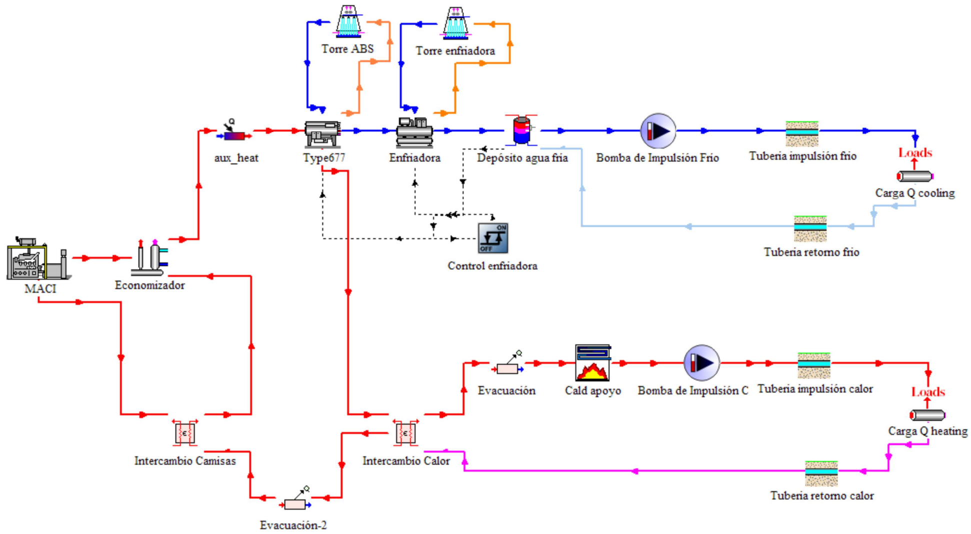

Figure 11: District heating and cooling model. Layout

Together with any potential technology that could be interesting to assess, the model provides alternative supply options based on conventional technologies, offering the opportunity of either comparing the selected technology against conventional ones or to evaluate the convenience of operating in an hybrid approach operating these conventional technologies in the first years and then investing in alternative solutions depending on the annual evolution of the thermal demand.

Techno-economic assessment

Finally, concerning the economic analysis, detailed spreadsheets are developed to evaluate the economic profit derived from the installation. The economic analysis is based on traditional indicators such as pay-back periods and net present value metrics, with the additional feature of considering variable cash flows depending again on the demand evolution and variable revenues linked to the amount of energy provided.

Conclusions

The application of the method to a specific case study indicates that thermal networks require long payback periods, more than 15 years. The analysis stresses the need to make profit from the co-production of electricity. This means that conventional generation of electricity based on mechanical compressor chillers to cover the cooling needs and gas boilers in the case of heating do not provide sufficient incomes. Even more, under the assumed regulatory scenario that offers additional incomes for the electricity co-generated, the continuous operation of the cogeneration unit increases the revenues. The impact of the continuous operation of the cogeneration unit is proven by comparing the steam turbine and internal combustion engines which operation modes were define as non-fixed capacity factor and fixed capacity factor respectively.

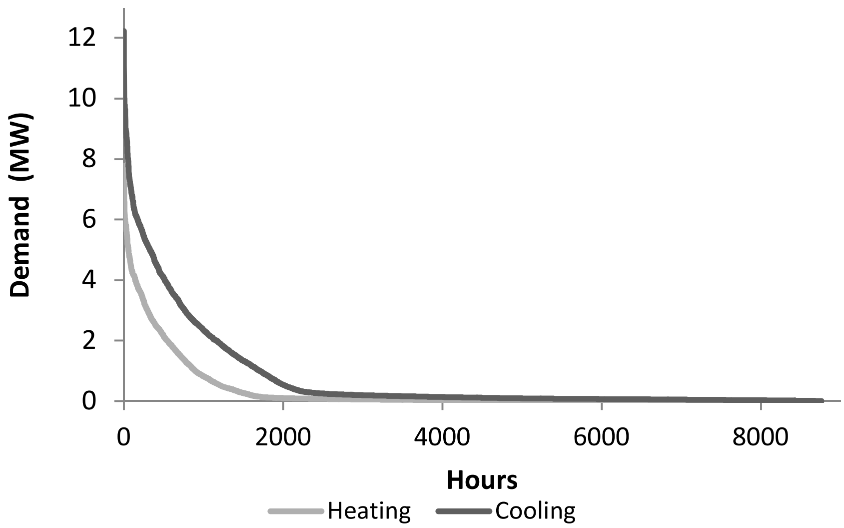

Figure 12: Load duration curves for heating and cooling demands

4.2 The effect of feed-in-tariff supporting schemes on the viability of a district heating and cooling production system

Juan Pablo Jiménez Navarro, José Manuel Cejudo López, David Connolly
Energy 134 (2017) 438 - 448

Author attribution

J.P. Jiménez-Navarro and J.M. Cejudo designed the study. J.P. Jiménez-Navarro developed the optimization model; J.M. Cejudo and D. Connolly validated the model; J.P. Jiménez-Navarro implemented the case study and performed the analysis; J.M. Cejudo validated the results; J.P. Jiménez with comment from the co-authors wrote the manuscript.

Context

This contribution represents a further step in the analysis presented in the previous paper. The conclusion drawn from the techno-economic analysis carried out in the previous study suggested that thermal networks requires supports or guarantees due to their long pay back periods and high level of upfront investments. Additionally, within the Spanish context, the energy policy failed when sizing the feed-in-tariffs support leading to energy costs that exceeded the allocated public budget and therefore to the sudden termination of any supporting schemes for efficient energy generation technologies, including combined heat and power to controlled the debt in the energy sector. This situation suggests that tailored support has to be designed per project, taking into consideration not only the benefit for the energy investor but also for the energy system and the society.

Scope

Therefore, the contribution aims to provide a method to size appropriate energy policy support in the form of feed-in-tariffs schemes in order to guarantee the feasibility of district heating and cooling networks fed by combined heat and power technologies. Put in different way, the method provides the optimal size of the energy equipment given a fixed feed-in-tariff scheme in place. Thus, both policymakers and energy investors can take advantage of the proposed method that will improve the understanding on the operation of thermal networks at district level, contributing to the establishment of public and private agreements needed to unlock the potential of district heating and cooling solutions.

Contributions

The proposed method relies on the implementation of a so-called energy superstructure or poly generation system, which have been studied in previous works [65, 82–84]. These systems include different energy generation technology options that could be combined in order to assess the optimal sizing and operation of the different components, supplying a given demand. For our purpose, the proposed poly generation system is depicted in Figure 13.

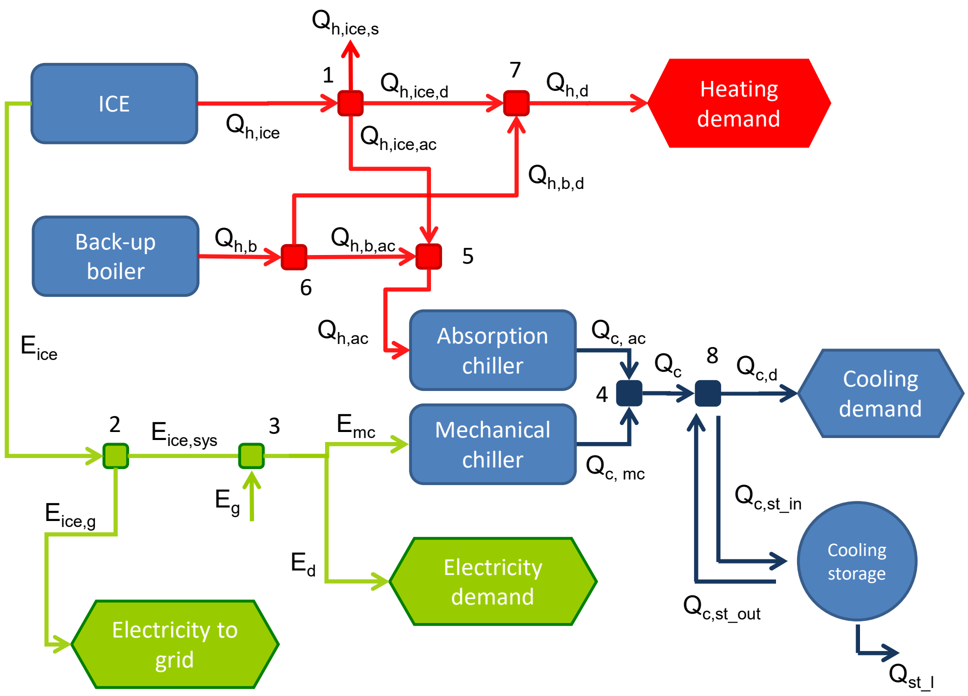

Figure 13: Scheme for a combined heating, cooling and power facility

The model compares two major scenarios; a centralized energy supply scenario based on the operation of CHP plants — internal com¬bustion engine — and, a decentralized energy supply scenario based on the op¬eration of conventional boilers and mechanical chillers. The additional feature of the proposed system, which has not been fully studied previously, is the link to the electricity market retail prices, including the cost of the purchased electricity from the grid and the price of electricity injected in the grid produced by the sys¬tem. This feature enables the possibility of generating electricity and selling it to the grid, or purchasing electricity from the grid to meet both the cooling demand, via mechanical chillers, and the electricity demand itself required for electric appliances. The system operates under a price-taker assumption, which means that the electricity market price is not affected by the potential electricity that could be injected from the system into the grid. This dependency with the electricity market prices allows understanding the impact of policy measures — feed-in-tariffs. Thus, given the electric market conditions and the energy demand, including heating, cooling and electricity, the model determines the optimal size and operation of the different equipment. If the conditions of the electricity market are not attractive enough, the optimal solution will include conventional technologies and electricity will be purchased from the grid to meet the electricity demand required — including the electricity needed to operate the mechanical chillers to supply the cooling needs. In addition, the structure provides the option of evaluating the role of cold storage that is expected to i) balance the short-term differences between cold supply and demand, ii) improve the performance of the energy generation technologies by enabling them to operate at better efficiencies and iii) reduce the need for extra generation capacity i.e. by supplying peak demands using the cold storage. Finally, the model includes additional equations to comply with policy regulations. For the case study assessment it is defined as minimum ratio between the electricity generated and the useful heat produced in the cogeneration unit, the so-called 'rendimiento eléctrico equivalente' (equivalent electric performance).

Conclusions

The study suggests that for the given case study (described in detail in section A), specific support is required to guarantee the feasibility of the co-generation system. Under no feed-in-tariff scenario, the optimal solution is based on conventional technologies. In addition it is also observed that the level of support required to provide positive revenues is close to the feed-in-tariffs set in the regulation (0.12 €/kWh). Fig 18 shows the relation between the price for the electricity injected in the grid and the revenues. However, it is clear that the support should be evaluated per project in order to ensure reasonable investment profits. The study shows how the daily thermal storage reduces peak demand. Therefore the required installed capacity decreases and does the upfront investment costs Another interesting conclusion derived from the study is the need for revisiting the conditions that ensure an efficient utilization of the co-generation system as a requisite to take advantage of the feed-in-tariffs. Thus, as defined for the Spanish case, lower COP efficiencies in the absorption chillers turn out to increase the useful heat produced in the cogeneration unit for the same amount of cold produced. This effect allows a higher production of electricity and thus higher economic benefit derived from the electricity injected in the grid. However, the overall efficiency of the system decreases. Therefore, the definition of the REE metric should be based on the final useful energy. So, instead of accounting the input heat in the absorption chillers as useful heat, it should account the useful cold produced in this conversion that takes place in the absorption chillers.

4.3 The joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system

Juan Pablo Jiménez Navarro, Konstantinos C. Kavvadias, Sylvain Quoilin, Andreas Zucker Energy 149 (2018) 535 – 549

Author attribution

K.C. Kavvadias and S. Quoilin have developed the background model; J.P. Jiménez-Navarro, K.C. Kavvadias and A. Zucker have defined the case study. J.P. Jiménez-Navarro have collected and processed all the input data required in the study; K.C. Kavvadias and J.P. Jiménez-Navarro have launched the simulations; J.P Jiménez-Navarro have processed the simulation results; J.P. Jiménez and K.C. Kavvadias with comment from the co-authors wrote the manuscript.

Context

This contribution is developed in the context of a growing share of energy generation from renewable sources within the power system. This trend is raising the need of sector coupling that enables the utilisation of a wider portfolio of energy technologies and thus accommodating a higher amount of intermittent renewables sources. In this regard, the heating sector — accounting for the 50% of the total final energy used in Europe and characterised by low efficiencies represents a great opportunity to couple with the power sector. This opportunity is highlighted in the European Strategy on Heating and Cooling [3].

To do so, the role of thermal networks becomes essential to connect centralised available energy sources with heating demand hubs [85]. Among others, the deployment of thermal networks may enable the use of waste heat sources and the use of high-efficient CHP technologies that could provide overall efficiencies of up to 90% [86]. Even more, under the new generation of district heating networks paradigm — the so called 4th generation of district heating — in which the operation temperatures are in the range of 30 — 70 C, CHP plants could provide even higher efficiencies.

Scope

Given all the above, in this work the conversion of a combined cycle gas turbines (CCGT) into a CHP operation mode in combination with centralised thermal storage option are modelled providing both electricity and heating by the connection to a thermal network. Thus, this model allows the evaluation of the impact of these solutions on the power systems, especially regarding the integration of high shares of renewables. The model approach also allows the evaluation of how the new generation of district heating systems contributes to the utilisation of these types of plants [14].

The integration of the proposed model on a power system dispatch model permits the evaluation of the cost reduction brought by the heating and electricity coupling via CHP and thermal storage.

Contributions

The major contribution of this work is the implementation of a model that includes the temperature as a parameter of design. This aspect allows the analysis of the benefit derived from the implementation of low temperature networks from the perspective of the CHP operation.

This model is based on the fact that in order to produce heat in the CHP part of the potential electricity produced has to be sacrificed. In this sense the CHP can be understood as a virtual heat pump and can be approximated by using the Carnot cycle expressions. shows the equivalent Carnot cycles for a steam turbine with and without extraction operations.

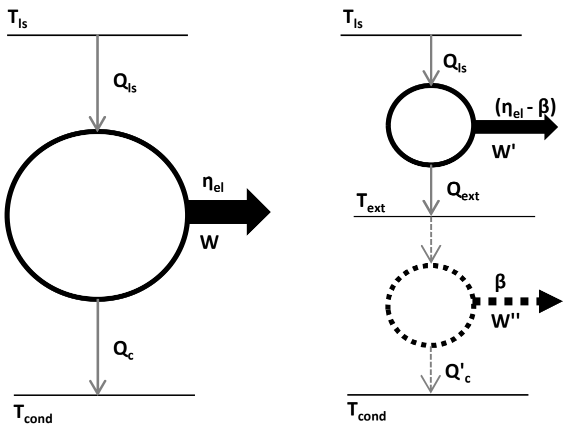

Figure 14: Steam cycle scheme. No extraction (a) and extraction (b) operations

Applying Carnot equations, the operation parameters of the steam turbine can be deducted (Eq. (2 —5) and the region of operation defined.

Table 4: Payback time for the different energy technologies

Parameter	**Mathematical expression**	**Eq.**
Power loss-ratio	$\beta = \frac{T_{ext} - T_{cond}}{T_{cond}}$	(3)
Power-to-heat ratio	$\sigma = \frac{\eta_{ise} \cdot 1 - \frac{T_{ext}}{T_{ls}}}{1 - \eta_{ise} \cdot 1 - \frac{T_{ext}}{T_{ls}}}$	(4)

The graphical representation of the region of operation is presented in Figure 15.

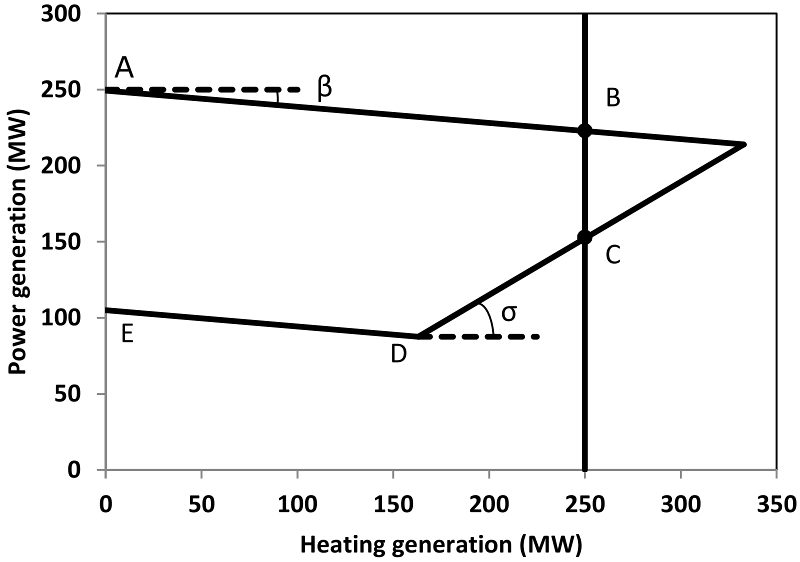

Figure 15: Feasible operation region for a CHP plant for a given DH input temperature

Additionally to the temperature dependant mode of the CHP plant, the model integrated into a power dispatch model — The DISPA-SET model [87] — offers the possibility of analysing how CHP plants can facilitate the penetration of higher share of renewables by assessing both the total cost and total efficiency of the energy power system.

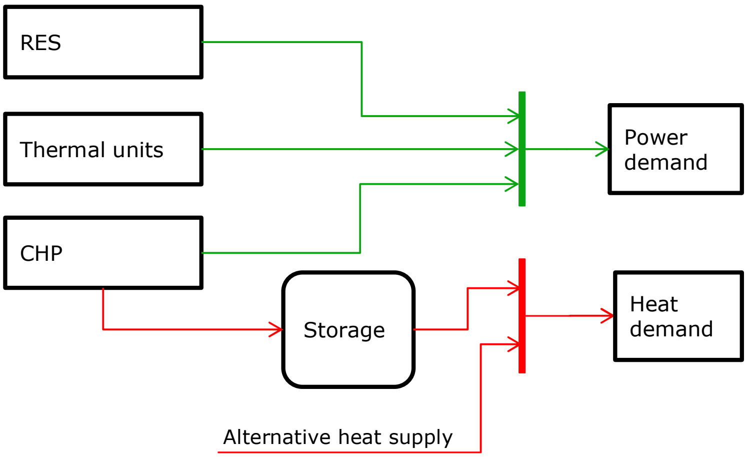

Figure 16: Integrated energy system for the coverage of specific power and heat demand

Contributions

Four different aspects have been evaluated with this study: i) the potential of the conversion of centralised combined cycle plants into centralised combined heat and power, ii) the role of thermal storage in the sector coupling, iii) the benefits provided by low temperatures of operation in thermal networks under the 4th generation of district heating paradigm and iii) the analysis of optimal scenarios by the combination of the aspects mentioned. Regarding the impact of the conversion of COMC into CHP, it brings an in¬crease in the total efficiency of the system and a cost reduction. The thermal storage enables higher capacity factors for the CHP plants and a high efficiency operation. In particular, for the high RES scenarios in which the op¬eration of the CHP is limited by the amount of RES to be incorporated in the system, the role of thermal storage becomes relevant in order to synchronise the heat produced by CHP and the heat demand. Another important contribution of this work is the evaluation of the impact of the temperature of extraction. According to the operation of the model proposed for the CHP plants, high temperatures of extraction in the plant lead to lower efficiencies. It is proven in the analysis that temperatures in the typical range of operation of 4GDH (30 — 70 C) increases the efficiency of the centralised CHP plants, reduces total costs of the system and increases the CO2 emissions. In addition, low temperature of extraction makes the heat provided by the CHP capable of competing with cheaper heat supply alternatives (AHS). In particular for exogenous AHS prices of 10 €/MWh, the share of heat demand supplied by

CHP plants varies from 10% (temperatures of extraction above 100 C) to 90% of the total heat demand for low temperature of extraction of the order of 60 C. Finally, given the implications among the different variables assessed, it was required to analysis the Pareto-optimal solutions in order to understand the trade-off between affordability — system costs — and efficiency. It is concluded that, the optimal scenario in terms of cost and efficiency results from the combination of high CHP penetration, operated at low temperature of extraction, available thermal storage under an scenario of high penetration of renewable energy.

Chapter 5

Conclusions and major contributions

This thesis aimed to explore opportunities and challenges that energy solutions at district level face in order to achieve higher penetration shares of renewable energy sources. The ultimate goal is to contribute to the decarbonisation of the heating sector, which accounts for half of the total final energy consumption in Europe. The research carried out provides energy investors and policy-makers with tools and methods to facilitate the evaluation of energy investments and the adequacy of policy measures.

The major motivation of this work is to contribute to the deployment of thermal networks in Southern European countries where, in contrast to Northern EU member states, these facilities are not widely used despite having a high potential.

The different scientific outputs presented prove that with an appropriate policy support and taking advantage of available energy options and applying them in high energy density areas, the deployment of thermal networks may unlock the benefits derived from a combined production of heating and electricity leading to:

1. an increased efficiency of the energy systems,
2. a more flexible energy system, acknowledged as a key aspect to integrate more renewable sources. In this matter, the research investigates the role of thermal storage in supporting this integration.

More specifically, the major motivations to carry out this study have been:

1. The implementation of a modelling framework and the comprehensive evaluation of the adequacy of thermal networks in non-consolidated areas with high potential energy needs in terms of energy demand density.

2. The development of a method to implement tailor-made measures to guarantee the success of the district heating and cooling business models.

3. The evaluation of the impact of the integration of the heating and cooling sectors in the power system to assess how this integration may accommodate larger renewable installed capacity, as expected in the coming years.

The major outcomes and conclusions derived from this thesis are presented in detail below:

Viability of a district heating and cooling network

This work highlights the importance of certain aspects that are relevant when sizing a thermal network; the existence of a supporting policy that ensures revenues from the electricity produced by the energy system and injected in the electricity grid, such as feed-in-tariffs or feed-in-premium; the impact of the uncertainty and future evolution of the energy demand in the area under consideration; and finally the need to combine different user profiles to level out the daily energy demand profiles and thus the load duration curves, leading to a more efficient operation of the energy generation technologies. Yet the high upfront investment costs, mostly related to construction of the networks themselves — 7.5 M€ for a 4km network considered in our study — have a negative impact on the payback period. Therefore, one of the main conclusions from this analysis is the need of setting public and private partnerships that ensure the operation of the networks and share or minimise the associated financial risks.

The effect of feed-in-tariff supporting schemes on the viability of a district heating and cooling production system

Combined heat and power systems can satisfy energy demands in a cost-effective way, especially in areas characterised by high intensity energy needs.

Driven by the outcomes obtained in the first scientific article discussed in section 4.1, and taking into consideration the high-risk investment required because of the cost of the installation and the stability of the energy demand in the long term, energy policies have been designed to promote the penetration of these installations. However, the significant increase in the installed capacity of energy technologies that benefited from the energy policies in place jeopardised the economic stability of the energy sector, endangering as well the feasibility of DHCs or even CCHP.

To facilitate energy investor decision making, this research presents a method to optimise the size of potential DHC/CCHP projects.

As presented in chapter 4, large scale CHP units that supply energy for districts still need policy support to guarantee its penetration in the energy market. However due to the limited financial sources available, it is important to properly design support schemes by ensuring the benefit for both energy investors and the public. In this regard, the method also allows policymakers to define appropriate feed-in-tariffs.

In the paper, the analysis of support schemes in the case study demonstrates it was well-defined. In addition, it is also demonstrates that FiTs improves the economics and efficiency of local systems by promoting the implementation of CHP together with thermal storage.

Nonetheless, the adequate definition of FiTs varies based on parameters selected for a particular project. In the case study, the coefficient of performance (COP) of mechanical chillers is the most sensitive parameter that may modify economic results by more than 10 c€ per euro invested and unitary COP increment. On the contrary, in the case of heating production, an improvement in the boiler performance has 4 times less impact compared to mechanical absorption chillers. These effects are linked to demand patterns.

Energy demand, it plays an important role in achieving feasibility as it has been demonstrated. Firstly, for cases where the energy demand varies significantly, on a daily basis, the only opportunity for CCHP systems relies on the production of a base load demand to guarantee the installation's steady performance. Secondly, demand evolution uncertainty can also prevent some investments, especially in tertiary areas linked to economic activities where demand may vary significantly.

Last, the case study proves that under specific investment and operational cost schemes, legal constraints defined to foster efficiency may have a negative effect (Rendimiento eléctrico equivalente). The effect of the absorption chillers performance supports the definition of legal constraints including the output cold produced by the absorption chillers instead of the input heat in the calculation of the useful thermal energy. Thus, the required ratio between this useful thermal energy and the electricity produced in ensured.

The joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system

We present a new method to assess the benefit derived from the conversion of existing steam-based turbine plants into combined heat and power plant has been presented in chapter 4. This method relies on the application of a unit commitment and dispatch model, which includes a detailed representation of the heating system, allowing the assessment of different assumptions such as energy prices, different share of installed capacities for a set of energy technologies and the operation of CHP plants. The ability of the method to link the optimisation of the energy system with the supply temperature delivered by the CHP plant is a valuable asset to evaluate different heat uses, such as the new 4th generation district heating systems characterised by low temperatures of operation, and the derived benefits.

The method has been tested in a small energy system, which offers opportunities to supply heat by the conversion of existing steam-based turbine plants into combined heat and power operation mode.

Results indicate that the conversion into combined heat and power plant leads to an increased efficiency of the energy system, which otherwise is limited to up to 50%. This effect relies on the higher efficiency of the CHP up to 90% for some operation points. However, the deployment of CHP may hinder the utilisation of renewable energy sources leading to renewable energy curtailment. The analysis presented demonstrates that this negative effect could be mitigated by the flexibility provided by thermal storage. However, there is a trade-off between the integration of high CHP and high RES simultaneously.

The analysis of different alternative heat costs reveals that CHP plants could compete with costs in the order of 10 €/MWh. However, for this low cost, the utilisation of the CHP decreases and so does the benefit offered by thermal storage options.

From the CHP operation perspective, low temperature of extraction leads to higher efficiencies and lower costs. Then, the lower the temperature required the better it is for the efficiency of the system. But this increases the amount of RES curtailed by 1% when the temperature of extraction increases from 60 to 120 °C if high RES scenarios are considered. In conclusion, the incorporation of CHP in combination with thermal storage in the energy system leads to high efficiencies and reduced costs. However, in high RES scenarios, this benefit limits the integration of renewables, despite the fact that it still reduces costs.

Table 5 summarizes the major outcomes achieved for the 3 pieces of work

Table 5: Scientific paper highlights

Paper	Highlights
Viability of a district heating and cooling network - section 4.1	A detailed dynamic model, including demand and generation, is implemented to assess the viability of thermal networks Long payback times are observed due to the construction of the thermal network that represents 75% of the total investment for the case study
The effect of feed-in-tariff supporting schemes on the viability of a district heating and cooling production system - section 4.2	An optimal sizing method for combined cooling, heat and power projects is proposed Combined cooling, heat and power projects at district level still require support Public support has to be specifically designed per project
The joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system - section 4.3	Model of centralised cogeneration plants with varying heat temperatures Co-optimization of heat and power using a unit commitment model CHP plants increase the affordability and the overall energy efficiency of the system Thermal storage reduces the curtailment of renewable while increasing the overall system efficiency CPH plants become more competitive by supplying heat to low temperature networks

Limitations of the thesis

When it comes to researching energy systems, the characterisation of the energy demand is a complex task. It requires assumptions on user and occupant behaviour. As a result, it is difficult to predict the actual energy needs. In this thesis, we approach the matter in a deterministic way. However, the conclusions could benefit from the use of stochastic approaches. We expect that new results using this type of stochastic approach could shed light on the statistical significance and representativeness of the results.

Recommendations for policy and practice

In terms of policies and applications on the future energy system, based on this work, three main recommendations can be formulated.

First, the deployment of thermal networks should be investigated in detail to connect demand and supply from centralised power plants. Geo spatial evaluation of feasible heat supply from real existing power plants to high density demand areas could provide a view of the actual potential of thermal networks. An analysis like this, across Europe, can stimulate the provision of input for energy policies that incorporate the use of available heat from centralised power plants.

Second, the need of supporting schemes, such as feed-in-tariffs, should be reevaluated in current energy policies. The subsidy of specific energy solutions has proven not to always be beneficial. However, based on this work, in the deployment of thermal networks in the South of Europe, a feed-in-tariff scheme could guarantee the viability of these solutions. Feed-in-tariff schemes should be deployed carefully as they are not "one size fits all" solution.

Last, electrification is gaining attention in the energy policy scene. Heat pump technologies, defined by high efficiency ratios, can contribute to the decarbonisation of the heating sector. In this matter, the combined evaluation of two different pathways in the heating sector, the use of heat from centralised power plants and the electrification at the demand side are worth investigating.

Recommendations for future research

As future research lines, according to the expected evolution of the energy system, many options are available to evaluate different technology portfolios in the process to integrate more options such as heat pumps or electric storage.

More specifically, 3 main lines are pursued;

1. The role of electric storage in the supply of thermal energy needs and its competitiveness against thermal storage. Electric storage costs have plunged in the last years. Its feasibility may unlock many more opportunities such as

the large deployment of heat pumps fed by renewable energies. However, the issue concerning the reliability of its performance has to be explored and considered when assessing energy systems. In this regard, some preliminary works have been already completed under the title "Optimal Home Battery Sizing and Dispatch in EU Countries Taking Into Account Battery Degradation and Self-Consumption Incentives" that was presented in the 11th International Renewable Energy Storage Conference (IRES 2017) [88].

2. The second research line concerns the evaluation of the operation of centralised CHP plants in combination with decentralised heat pumps, also known as booster heat pumps. The aim of this working line is the evaluation of how high-efficient heat pumps may expand the utilisation of low temperature sources and how they can be operated in combination with centralised extraction/condensing turbines to maximise efficiency and minimise costs.

3. Last, the third line focuses on the definition of a metric for thermal storage, analogous to the levelised cost of energy for generation technologies, to facilitate the analysis of the convenience of incorporating thermal storage in different district heating and cooling applications and promote its utilisation. Literature review only shows some studies for electric storage.

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Appendix A

Scientific output

Viability of a district heating and cooling network
Juan Pablo Jiménez Navarro, Rogelio Zubizarreta Jiménez, José Manuel Cejudo López
DYNA 87 (2012) 305 - 315

Author attribution

R. Zubizarreta and J.M. Cejudo designed the goals of the study; J.P. Jiménez-Navarro and R. Zubizarreta developed the methodology to characterize the demand and the implementation of the building models used in the study; J.P. Jiménez-Navarro and R. Zubizarreta designed and set up the energy generation models and the techno-economic assessment; J.P. Jiménez-Navarro performed the analysis; J.M. Cejudo validated the results of the study; J.P. Jiménez (with comments from the co-authors) wrote the manuscript.

Abstract

The purpose of this paper is to present the results of the feasibility study for a district heating-cooling network to cover the energy demand in a Scientifi c and Technological Park under Mediterranean climate conditions. This study consists of three phases: energy demand, technology analysis and economic study. To evaluate the energy demand a bottom-up strategy has been followed: a building inventory has been carried out to defi ne several building types according to use, envelope and glazing. Energy + has been used to obtain heating and cooling demand profi les for each building type and orientation. According to municipal development plans for PTA and forecast in business growth, the energy demand evaluation in

a 10-years timeframe has been carried out. Most appropriate technologies has been analyzed and evaluated: cogeneration (gas turbine and alternative internal combustion engines), biomass boiler and conventional technologies have been evaluated with TRNSYS to obtain consumption profi les, consumption rates, effi ciency indicators and energy losses. Finally an economic analysis has been done to technologies in a 20 years period to evaluate technology that better economic results address. The main objective of this work is the promotion of the effi cient and effective energy supply in areas with high energy consumption. DCH technology is widely used in the North of Europe and this paper tries to demonstrate that this technology could be applied in Mediterranean areas successfully.

DOI

http://dx.doi.org/10.6036/4449

The effect of feed-in-tariff supporting schemes on the viability of a district heating and cooling production system

Juan Pablo Jiménez Navarro, José Manuel Cejudo López, David Connolly

Energy 134 (2017) 438 - 448

Author attribution

J.P. Jiménez-Navarro and J.M. Cejudo designed the study. J.P. Jiménez-Navarro developed the optimization model; J.M. Cejudo and D. Connolly validated the model; J.P. Jiménez-Navarro implemented the case study and performed the analysis; J.M. Cejudo validated the results; J.P. Jiménez with comment from the co-authors wrote the manuscript.

Abstract

Combined cooling, heat and power systems represent an efficient alternative to supply heating and cooling demand compared to conventional boilers and air conditioner systems. However, considering the high level of upfront investment and the relatively long lifetimes, it is important to provide some form of long-term certainty to reduce the risk of deployment of these systems. To overcome this uncertainty, this paper describes a method to calculate an appropriate feed-in-tariff scheme to support investors and public authorities to foster the penetration of this technology in areas with high energy demands. It is subsequently tested in a scientific and technology park located in the south of Spain where different energy prices are studied. The results indicate that a feed-in-tariff is required to support the development of combined heating, cooling, and power systems, which not only improves the economic performance of the system, but also increases the utilisation of more efficient generation technologies such as combined cooling, heat and power systems.

DOI

http://dx.doi.org/10.1016/j.energy.2017.05.174

The joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system Juan Pablo Jiménez Navarro, Konstantinos C. Kavvadias, Sylvain Quoilin, Andreas Zucker Energy 149 (2018) 535 - 549

Author attribution

K.C. Kavvadias and S. Quoilin have developed the background model; J.P. Jiménez-Navarro, K.C. Kavvadias and A. Zucker have defined the case study. J.P. Jiménez-Navarro have collected and processed all the input data required in the study; K.C. Kavvadias and J.P. Jiménez-Navarro have launched the simulations; J.P Jiménez-Navarro have processed the simulation results; J.P. Jiménez and K.C. Kavvadias with comment from the co-authors wrote the manuscript.

Abstract

The coupling of the heating and the electricity sectors is of utmost importance when it comes to the achievement of the decarbonisation and the energy efficiency targets set for the 2020 and 2030 in the EU. Centralised cogeneration plants connected to district heat networks are fundamental element of this coupling. Despite the efficiency benefits, the effects of introducing combined generation to the power system are sometimes adverse. Reduced flexibility caused by contractual obligations to deliver heat may not always facilitate the penetration of renewable energy in the energy system. Thermal storage is acknowledged as a solution to the above. This work investigates the optimal operation of cogeneration plants combined with thermal storage. To do so, a combined heat and power (CHP) plant model is formulated and incorporated into Dispa-SET, a JRC in-house unit commitment and dispatch model. The cogeneration model sets technical feasible operational regions for different heat uses defined by temperature requirements. Different energy system scenarios are used to assess the implications of the heatingeelectricity coupling to the flexibility of the power system and to the achievement of the decarbonisation goals in an existing non interconnected power system where CHP plants provide heating and electricity to nearby energy dense areas. The analysis indicates that the utilisation of CHP plants contributes to improve the overall system efficiency and reduce total cost of the system. In addition, the incorporation of thermal storage increases the penetration of renewable energy in the system.

DOI

https://doi.org/10.1016/j.energy.2018.02.025