Market Power with Combined Heat and Power Production in the Nordic Energy System

Vilma Virasjoki, Afzal S. Siddiqui, Behnam Zakeri, and Ahti Salo

Abstract—The trend toward increasing energy efficiency and variable renewable energy (VRE) production has implications for combined heat and power (CHP) plants, which operate in both the price-driven power market and the district heating (DH) sector. Since CHP will be important in VRE integration, we develop a complementarity model to analyze CHP producers' roles in integrated markets. We use a Nordic case study to gain insights into (i) the effect of the link between CHP and DH on market power and (ii) market power's impact on operations in the DH sector. The results indicate that (i) the link of CHP to DH supply can increase market power and (ii) market power can induce shifts in DH production from heat-only to CHP.

NOMENCLATURE

Indices and Sets

$e \in \mathcal{E} := \{\text{wind, solar}\}$: Variable renewable energy (VRE) sources
$i \in \mathcal{I}$: Producers
$\ell \in \mathcal{L}$: Power lines
$\ell^{\text{AC}} \in \mathcal{L}^{\text{AC}} \subset \mathcal{L}$: AC power lines
$\ell^{\text{DC}} \in \mathcal{L}^{\text{DC}} \subset \mathcal{L}$: DC power lines
$n \in \mathcal{N}$: Nodes
$n^{\text{AC}} \in \mathcal{N}^{\text{AC}} \subset \mathcal{N}$: Nodes connected to AC lines
$n^{\text{DC}} \in \mathcal{N}^{\text{DC}} \subset \mathcal{N}$: Nodes connected only to DC lines
$t \in \mathcal{T}$: Time periods
$u \in \mathcal{U}$: Power-only unit types
$x \in \mathcal{X}$: Heat-only unit types
$y \in \mathcal{Y}$: Combined heat and power (CHP) unit types
$y^{\text{B}} \in \mathcal{Y}^{\text{B}} \subset \mathcal{Y}$: Back-pressure CHP unit types
$y^{\text{E}} \in \mathcal{Y}^{\text{E}} \subset \mathcal{Y}$: Extraction CHP unit types
$u \in \mathcal{U}_{n,i}$: Power-only units of producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$
$x \in \mathcal{X}_{n,i}$: Heat-only units of producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$

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$y \in \mathcal{Y}_{n,i}$: CHP units of producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$

$\mathcal{L}^{\text{AC}} \cup \mathcal{L}^{\text{DC}} = \mathcal{L}$, $\mathcal{L}^{\text{AC}} \cap \mathcal{L}^{\text{DC}} = \emptyset$, $\mathcal{N}^{\text{AC}} \cup \mathcal{N}^{\text{DC}} = \mathcal{N}$.

Parameters

$A_{n,t}^e$: Availability factor of VRE $e \in \mathcal{E}$ at node $n \in \mathcal{N}$ during period $t \in \mathcal{T}$ (-)
$C_{n,u,t}^{\text{power}}$: Generation cost of power-only unit $u \in \mathcal{U}_{n,i}$ of producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ in period $t \in \mathcal{T}$ (€/MWh)
C_x^{heat}: Generation cost of heat-only unit $x \in \mathcal{X}_{n,i}$ (€/MWh$_{th}$)
$C_y^{\text{chp,p}}$: Electricity generation cost of CHP unit $y \in \mathcal{Y}_{n,i}$ (€/MWh)
$C_y^{\text{chp,h}}$: Heat generation cost of CHP unit $y \in \mathcal{Y}_{n,i}$ (€/MWh$_{th}$)
$D_{n,t}^{\text{int}}$: Intercept of linear inverse demand function at node $n \in \mathcal{N}$ during period $t \in \mathcal{T}$ (€/MWh)
$D_{n,t}^{\text{slp}}$: Slope of linear inverse demand function at node $n \in \mathcal{N}$ during period $t \in \mathcal{T}$ (€/MWh^2)
E^{eff}: Heat storage input efficiency (-)
E^{dec}: Rate of decay in heat storage per hour (-)
$E^{\text{in}}/E^{\text{out}}$: Heat storage charge/discharge rate (MW$_{th}$/MWh$_{th}$)
$\overline{E}_{n,i}^{\text{max}}/\underline{E}_{n,i}^{\text{min}}$: Heat storage maximum/minimum capacity of producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (MWh$_{th}$)
E_n^{trans}: Heat transmission efficiency within node $n \in \mathcal{N}$ (-)
$\overline{F}_{y^{\text{E}}}$: Maximum fuel intake of extraction CHP unit $y^{\text{E}} \in \mathcal{Y}^{\text{E}}$ (MWh)
$\overline{G}_{n,i,u}^{\text{power}}$: Capacity of power-only unit $u \in \mathcal{U}_{n,i}$ of producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (MW)
$\overline{G}_{n,i,x}^{\text{heat}}$: Capacity of heat-only unit $x \in \mathcal{X}_{n,i}$ of producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (MW$_{th}$)
$\overline{G}_{n,i,y}^{\text{chp,h}}$: Maximum heat capacity of CHP unit $y \in \mathcal{Y}_{n,i}$ of producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (MW$_{th}$)
$\overline{G}_{n,i}^e$: Capacity of VRE type $e \in \mathcal{E}$ of producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (MW)
$H_{\ell^{\text{AC}},n}$: Element (ℓ^{AC}, n) of network transfer matrix; the susceptance on line $\ell^{\text{AC}} \in \mathcal{L}^{\text{AC}} \subset \mathcal{L}$ to node $n \in \mathcal{N}$ in the AC part of the network (1/Ω)
$\overline{K}_\ell/\underline{K}_\ell$: Capacity of power line $\ell \in \mathcal{L}$ in +/- direction (MW)
$M_{\ell,n}$: Incidence matrix of the grid topology; the start (-1) and end (+1) nodes $n \in \mathcal{N}$ of line $\ell \in \mathcal{L}$ (-)
P_n^{heat}: Heat price at node $n \in \mathcal{N}$ (€/MWh$_{th}$)
$Q_{n,i,t}^{\text{heat}}$: Heat sales by producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ during period t (MWh$_{th}$)
$R_{y^{\text{B}}}^{\text{p-t-h}}/R_{y^{\text{E}}}^{\text{p-t-h}}$: Power-to-heat ratio of back-pressure CHP type $y^{\text{B}} \in \mathcal{Y}^{\text{B}}$ or extraction CHP type $y^{\text{E}} \in \mathcal{Y}^{\text{E}}$ (MWh/MWh$_{th}$)
$R_{y^{\text{E}}}^{\text{f-t-h}}$: Fuel-to-heat ratio of CHP type $y^{\text{E}} \in \mathcal{Y}^{\text{E}}$ (MWh/MWh$_{th}$)
$R_{y^{\text{E}}}^{\text{f-t-p}}$: Fuel-to-power ratio of CHP type $y^{\text{E}} \in \mathcal{Y}^{\text{E}}$ (-)
$R_{n,i}^{\text{heat-only}}$: Minimum share of district heating (DH) to be met

by heat-only generation for (fringe) producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ (-)

$R_u^{\text{power-up}}/R_u^{\text{power-down}}$: Ramp limits for power-only unit $u \in \mathcal{U}$ (-)

$R_x^{\text{heat-up}}/R_x^{\text{heat-down}}$: Ramp limits for heat-only unit $x \in \mathcal{X}$ (-)

$R_y^{\text{chp-up}}/R_y^{\text{chp-down}}$: Ramp limits for CHP unit $y \in \mathcal{Y}$ (-)

$S_{n^{\text{AC}}} \in \{0,1\}$: Definition of the slack node, $n^{\text{AC}} \in \mathcal{N}^{\text{AC}}$ (-)

T_t: Length of period $t \in \mathcal{T}$ (h)

Primal Variables

$f_{\ell,t}$: Power flow on line $\ell \in \mathcal{L}$ during period $t \in \mathcal{T}$ (MW)

$g_{n,i,u,t}^{\text{power}}$: Electricity-only generation at node $n \in \mathcal{N}$ by producer $i \in \mathcal{I}$ using $u \in \mathcal{U}_{n,i}$ during period $t \in \mathcal{T}$ (MWh)

$g_{n,i,x,t}^{\text{heat}}$: Heat-only generation at node $n \in \mathcal{N}$ by producer $i \in \mathcal{I}$ using $x \in \mathcal{X}_{n,i}$ during period $t \in \mathcal{T}$ (MWh$_{th}$)

$g_{n,i,y,t}^{\text{chp,p}}$: CHP electricity generation at node $n \in \mathcal{N}$ by producer $i \in \mathcal{I}$ using $y \in \mathcal{Y}_{n,i}$ during period $t \in \mathcal{T}$ (MWh)

$g_{n,i,y,t}^{\text{chp,h}}$: CHP heat generation at node $n \in \mathcal{N}$ by producer $i \in \mathcal{I}$ using $y \in \mathcal{Y}_{n,i}$ during period $t \in \mathcal{T}$ (MWh$_{th}$)

$g_{n,i,t}^{e}$: VRE electricity generation at node $n \in \mathcal{N}$ by producer $i \in \mathcal{I}$ using $e \in \mathcal{E}$ during period $t \in \mathcal{T}$ (MWh)

$q_{n,i,t}^{\text{power}}$: Electricity sales at node $n \in \mathcal{N}$ by producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (MWh)

$r_{n,i,t}^{\text{sto}}$: Stored heat at node $n \in \mathcal{N}$ by producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (MWh$_{th}$)

$r_{n,i,t}^{\text{in}}/r_{n,i,t}^{\text{out}}$: Charged/discharged heat at node $n \in \mathcal{N}$ by producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (MWh$_{th}$)

$\theta_{n^{\text{AC}},t}$: Voltage angle at node $n^{\text{AC}} \in \mathcal{N}^{\text{AC}}$ during period $t \in \mathcal{T}$ (rad)

Dual Variables

$\beta_{n,i,t}^{\text{bal}}$: Shadow price of heat storage balance constraint at node $n \in \mathcal{N}$ by producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (€/MWh$_{th}$)

$\beta_{n,i,t}^{\text{in}}/\beta_{n,i,t}^{\text{out}}$: Shadow price of heat storage charge/discharge constraint at node $n \in \mathcal{N}$ by producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (€/MWh$_{th}$)

$\beta_{n,i,t}^{\text{lb}}/\beta_{n,i,t}^{\text{ub}}$: Shadow price of heat storage minimum/maximum capacity constraint at node $n \in \mathcal{N}$ by producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (€/MWh$_{th}$)

$\gamma_{n^{\text{AC}},t}$: Shadow price of slack node $n^{\text{AC}} \in \mathcal{N}^{\text{AC}}$ during period $t \in \mathcal{T}$ (-)

$\eta_{\ell^{\text{AC}},t}$: Shadow price of loop-flow constraint on AC lines $\ell^{\text{AC}} \in \mathcal{L}^{\text{AC}}$ during period $t \in \mathcal{T}$ (€/MWh)

$\delta_{i,t}^{\text{power}}$: Shadow price of electricity balance of producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (€/MWh)

$\delta_{n,i,t}^{\text{heat}}$: Shadow price of heat balance of producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ during period $t \in \mathcal{T}$ (€/MWh$_{th}$)

$\delta_{n,i,t}^{\text{heat-only}}$: Shadow price of minimum heat-only/DH ratio, producer $i \in \mathcal{I}$ at node $n \in \mathcal{N}$ during period $t \in \mathcal{T}$ (€/MWh$_{th}$)

$\lambda_{n,i,u,t}^{\text{power}}$: Shadow price of power-only capacity at node $n \in \mathcal{N}$ of producer $i \in \mathcal{I}$ for type $u \in \mathcal{U}_{n,i}$ during period $t \in \mathcal{T}$ (€/MWh)

$\lambda_{n,i,y,t}^{\text{chp,h}}$: Shadow price of CHP heat capacity at node $n \in \mathcal{N}$ of producer $i \in \mathcal{I}$ for type $y \in \mathcal{Y}_{n,i}$ during period $t \in \mathcal{T}$ (€/MWh$_{th}$)

$\lambda_{n,i,x,t}^{\text{heat}}$: Shadow price of heat-only capacity at node $n \in \mathcal{N}$

of producer $i \in \mathcal{I}$ for type $x \in \mathcal{X}_{n,i}$ during period $t \in \mathcal{T}$ (€/MWh$_{th}$)

$\lambda_{n,i,t}^{e}$: Shadow price of VRE capacity at node $n \in \mathcal{N}$ of producer $i \in \mathcal{I}$ for type $e \in \mathcal{E}$ during period $t \in \mathcal{T}$ (€/MWh)

$\overline{\mu}_{\ell,t}/\underline{\mu}_{\ell,t}$: Shadow price of transmission capacity on line $\ell \in \mathcal{L}$ in +/- direction during period $t \in \mathcal{T}$ (€/MWh)

$\rho_{n,i,u,t}^{\text{power-up}}/\rho_{n,i,u,t}^{\text{power-down}}$: Shadow price of ramping up/down power generation $u \in \mathcal{U}_{n,i}$ at node $n \in \mathcal{N}$ of producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (€/MWh)

$\rho_{n,i,x,t}^{\text{heat-up}}/\rho_{n,i,x,t}^{\text{heat-down}}$: Shadow price of ramping up/down heat-only generation $x \in \mathcal{X}_{n,i}$ at node $n \in \mathcal{N}$ of producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (€/MWh$_{th}$)

$\rho_{n,i,y,t}^{\text{chp-up}}/\rho_{n,i,y,t}^{\text{chp-down}}$: Shadow price of ramping up/down CHP generation $y \in \mathcal{Y}_{n,i}$ at node $n \in \mathcal{N}$ of producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (€/MWh$_{th}$)

$\phi_{n,i,y^{\text{B}},t}^{\text{B}}$: Shadow price of power-to-heat constraint of back-pressure CHP unit $y^{\text{B}} \in \mathcal{Y}_{n,i}^{\text{B}}$ at node $n \in \mathcal{N}$ of producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (€/MWh)

$\phi_{n,i,y^{\text{E}},t}^{\text{E,p-t-h}}$: Shadow price of power-to-heat constraint of extraction CHP unit $y^{\text{E}} \in \mathcal{Y}_{n,i}^{\text{E}}$ at node $n \in \mathcal{N}$ of producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (€/MWh)

$\phi_{n,i,y^{\text{E}},t}^{\text{E,ub-fuel}}$: Shadow price of maximum fuel intake constraint of extraction CHP unit $y^{\text{E}} \in \mathcal{Y}_{n,i}^{\text{E}}$ at node $n \in \mathcal{N}$ of producer $i \in \mathcal{I}$ during period $t \in \mathcal{T}$ (€/MWh)

$\omega_{n,t}$: Shadow price of power market-clearing condition at node $n \in \mathcal{N}$ during period $t \in \mathcal{T}$ (€/MWh)

I. INTRODUCTION

A. Background

Energy markets in the European Union (EU) are undergoing a paradigm shift. First, climate policy incentivizes power companies to adopt variable renewable energy (VRE), e.g., solar photovoltaic (PV) and wind power [1]. Since these non-dispatchable and decentralized energy sources can increase balancing needs, power markets are becoming more inter-connected [2]. Second, energy efficiency is critical in clean-energy endeavors [3], whereby tightening requirements call for technological innovations. This may mean investments in combined heat and power (CHP) plants together with district heating (DH) network extensions. The importance of the DH sector is highlighted by the fact that heating comprises about 50% of the global final energy demand [4].

Given this background, CHP has been proposed in the EU as a linchpin for reducing greenhouse gas emissions [5]. Because CHP uses excess heat from power production, its resource efficiency is *circa* (ca.) 90%, in contrast to ca. 40% with power-only generation. Finland and Denmark are leaders in CHP use with about 75% of DH and ca. 35% and 50% of annual power production covered by CHP, respectively [6]. Moreover, 75% of the DH capacity in these two countries is based on CHP. Even in a hydro- and nuclear-rich country like Sweden, CHP comprises over 10% of the installed power capacity. Additionally, from the perspective of concentration of ownership, only 20 CHP plants in Denmark and 47 in Finland account for 70% and 68%, respectively, of the total installed CHP power capacity. In other words, large power companies have the market share to exert market power, i.e.,

withhold output in order to raise prices. Thus, combined with the ambitious energy-efficiency, carbon-reduction, and VRE targets of the EU, CHP is likely to play a large role in future energy systems [7], and it would be prudent for policymakers to assess how CHP facilitates producers' use of market power and its implications for the DH sector.

B. Literature Review

In the Nordic countries, CHP operations face asymmetric regulations: the power price is determined by day-ahead and intraday markets in Nord Pool, while heat is supplied to consumers at contract-based long-term prices. Due to the DH sector's naturally dominant market position, the pricing decisions are limited by antitrust legislation and authority supervision [8]. The coordinated planning problem and the resulting feasible operating region (FOR) for CHP has been discussed as a multi-commodity robust optimization problem using unit commitment [9]. Another approach is taken to use a hierarchical stochastic setup to model CHP operations under uncertainty [10] resulting in a bi-level formulation that allows heat dispatch at the upper level, while modeling the day-ahead power market at the lower level. [11] and [12] focus on developing algorithms for solving hourly CHP operations with convex three-dimensional FORs efficiently, and Wu and Rosen [13] implement an equilibrium model to show the benefits of CHP on social welfare under perfect competition.

Chen et al. [14] examine how CHP with electric boilers and heat storage can provide system flexibility with VRE integration by developing a linear model with a convex CHP FOR (Fig. 1). On a related note, Hellmers et al. [15] show that the coordination between CHP and wind in a portfolio maximizes the expected profit for a producer in a two-price structure of the balancing market, and [16] studies the role of heat pumps and regulating CHP to integrate excess wind into the system in liberalized power markets. Overall, the DH sector can improve the performance of energy systems under a high VRE share [17], [18].

In spite of ongoing VRE adoption, most energy systems are based on large companies' conventional production decisions. Under perfect competition, the market price of a commodity is set by the marginal cost of production. In reality, a few power companies typically own sufficient generation capacity to exert market power, i.e., raise equilibrium prices, by withholding production. Under the Cournot assumption, each producer behaves as if other producers will not alter their generation [19]. Furthermore, a solution in which (i) each producer satisfies its first-order conditions for profit maximization while (ii) simultaneously meeting its constraints and ensuring the industry supply equals demand is a market equilibrium, which is referred to as a Nash equilibrium when no producer has the incentive to deviate unilaterally from this solution. The Cournot assumption together with the Nash equilibrium leads to the Nash-Cournot game-theoretic framework [20]. Besides the potential for production withholding in the power sector alone, the link between heat and power in the Nordic region provides additional flexibility to power companies to exert market power.

Given the increasing penetration of VRE, CHP capacity is likely to play a prominent role, which necessitates a careful analysis of its implications for market power. Indeed, evidence of post-deregulation market power has emerged, e.g., from the U.K. [21]. While there is no evidence of systematically higher-than-marginal-cost prices in Nord Pool, there can be regional market power due to insufficient transmission capacity, high national market concentration, and vertical integration. Thus, Nordic market power needs to be studied also from the perspective of base-load capacity withholding, e.g., plants' maintenance timing and hydropower reservoir use [22].

C. Research Objectives and Contribution

While complementarity models have been applied to study deregulated power industries [20], the asymmetric link of CHP to both power and DH supply has rarely been addressed. Especially in DH-intensive countries, models without the DH sector overlook an important part of energy systems. In particular, the complementarity approach enables us to examine system-wide impacts of CHP with the possibility of strategic market power use. Furthermore, network effects have become more significant because of VRE integration: the CHP equilibrium models by [13] and [10] ignore network effects, and Wu and Rosen [13] do not consider either VRE or market power.

We develop a complementarity model to study the role of CHP in the Nordic day-ahead market with ramping and transmission constraints. Indeed, complementarity modeling is flexible enough to assess market designs with increasing VRE shares, energy storage, and the gas market, e.g., [23]–[27]. This provides a framework that is appropriate for the research question (CHP's impact on market power) and the case study (Nordic region) because:

- Markets are cleared in the Nordic region as in the rest of Western Europe without unit commitment [25], [28]. Thus, in order to provide credible insights, our model needs to reflect market operations.
- Including market power in unit-commitment models involves the addition of side constraints that mimic strategic behavior, e.g., enforcing that marginal revenue is greater than or equal to marginal cost only if the unit is committed [29]. As [19] explains, such a constraint could become unwieldy for multi-period models as the marginal revenue may drop below the marginal cost for committed units during off-peak periods depending on the fixed costs.

Given its high overall energy efficiency, CHP is likely to be a part of DH-intensive countries' low-carbon futures. Nevertheless, coupled heat and power markets along with producers' ability to exert market power may hinder VRE integration if CHP's role is not fully understood. Consequently, we provide insights on market power's effects in such a system.

We use Nordic data to implement a case study of how (i) market power is impacted by CHP and (ii) market power can affect DH supply. We find that (i) not only can CHP intensify market power, but also (ii) market power can shift DH production between heat-only and CHP capacity. Thus, our model explicates CHP operations within the changing energy system and offers policy insights into the roles of different energy production types. The rest of this paper is structured
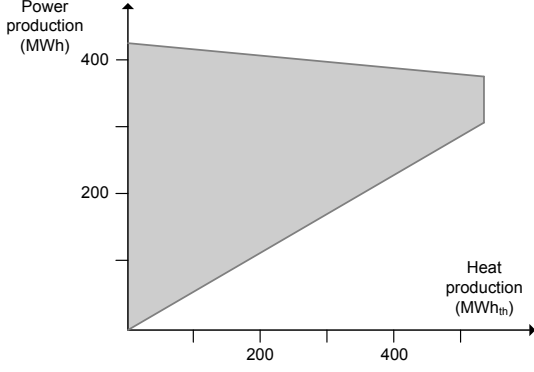
Fig. 1. A simplified feasible operating region for a coal extraction CHP unit.

as follows: Section II develops the mathematical formulation, Section III provides numerical examples for the Nordic energy system, and Section IV concludes.

II. PROBLEM FORMULATION

A. Decision-Making Problems

1) Producers $i \in \mathcal{I}$: Producers may own and operate conventional power capacity $u \in \mathcal{U}_{n,i}$, CHP capacity $y \in \mathcal{Y}_{n,i}$, heat-only capacity $x \in \mathcal{X}_{n,i}$, and VRE capacity $e \in \mathcal{E}$ at any node $n \in \mathcal{N}$ of the network. There are two types of CHP plants: back-pressure ($y^{\mathrm{B}} \in \mathcal{Y}^{\mathrm{B}} \subset \mathcal{Y}$) and extraction units ($y^{\mathrm{E}} \in \mathcal{Y}^{\mathrm{E}} \subset \mathcal{Y}$). Back-pressure CHP plants have a linear dependency between heat and power production, determined by a power-to-heat ratio, $R_{y^{\mathrm{B}}}^{\mathrm{p\text{-}t\text{-}h}}$. Extraction plants are modeled via a simplified FOR as in [10] (see Fig. 1).[1]

Power from either $u \in \mathcal{U}_{n,i}$ or $y \in \mathcal{Y}_{n,i}$ can be sold at the production node or transmitted at a cost $\omega_{n,t}$ and sold elsewhere (à la [19]); heat is consumed at the production node. The transmission loss associated with heat, E_n^{trans}, is the difference between production and supply at node n. The heat price, P_n^{heat}, and hourly sales of producers, $Q_{n,i,t}^{\mathrm{heat}}$, are fixed and known by market participants because they are based on bilateral contracts. To account for DH centralization, $R_{n,i}^{\mathrm{heat\text{-}only}}$ sets a minimum share of supply to be covered by heat-only. Producers can also own heat storage capacity, $\overline{E}_{n,i}^{\mathrm{max}}$, which can be charged with heat-only or CHP. There are no operating costs for storing heat, but efficiency losses in charging and from hourly decay are taken into account along with charging and discharging rates.

Although VRE production is a decision variable, $g_{n,i,t}^{e}$, it is de facto exogenous and determined by the availability factors, $A_{n,t}^{e}$, for each resource type. VRE also has zero marginal costs and priority grid access. Hydropower variations are captured

[1]Such an FOR is simplified compared to that in [14] because it neglects minimum power output constraints for active CHP units (likewise for power-only plants). However, since we model aggregated plant types at each node by firm, minimum power output constraints are less critical for accurate system representation than they would have been if we were modeling a single or a few distinct CHP units. Furthermore, including such constraints would require binary variables to model. Unfortunately, this would not enable the application of the complementarity framework and make it challenging to conduct an analysis of market power. Thus, we use a simplified FOR [10] and verify *ex post* that both CHP and power-only plants that are operational predominantly run at above their minimum power output levels (see Section III-C).

by the maximum available capacity, $\overline{G}_{n,i,u}^{\mathrm{power}}$, which depends on the season. Marginal costs of power production, $C_{n,u,t}^{\mathrm{power}}$, are hour-dependent for hydro (water value and load following) but constant for other technologies.

The objective function of producer $i \in \mathcal{I}$ is to maximize profits (1) from the sales and production of power and heat, inclusive of congestion fees, $\omega_{n,t}$, for power transmission:

$$\min_{\Gamma} \sum_{t \in \mathcal{T}} \sum_{n \in \mathcal{N}} \Bigg[- \left(D_{n,t}^{\mathrm{int}} - D_{n,t}^{\mathrm{slp}} \sum_{i' \in \mathcal{I}} q_{n,i',t}^{\mathrm{power}} - \omega_{n,t} \right) q_{n,i,t}^{\mathrm{power}}$$
$$- P_n^{\mathrm{heat}} Q_{n,i,t}^{\mathrm{heat}} + \sum_{u \in \mathcal{U}_{n,i}} \left(C_{n,u,t}^{\mathrm{power}} - \omega_{n,t} \right) g_{n,i,u,t}^{\mathrm{power}}$$
$$+ \sum_{x \in \mathcal{X}_{n,i}} C_x^{\mathrm{heat}} g_{n,i,x,t}^{\mathrm{heat}} + \sum_{y \in \mathcal{Y}_{n,i}} \left(C_y^{\mathrm{chp,p}} - \omega_{n,t} \right) g_{n,i,y,t}^{\mathrm{chp,p}}$$
$$+ \sum_{y \in \mathcal{Y}_{n,i}} C_y^{\mathrm{chp,h}} g_{n,i,y,t}^{\mathrm{chp,h}} - \omega_{n,t} \sum_{e \in \mathcal{E}} g_{n,i,t}^{e} \Bigg] \tag{1}$$

$$\text{s.t.} \sum_{n \in \mathcal{N}} q_{n,i,t}^{\mathrm{power}} - \sum_{n \in \mathcal{N}} \sum_{u \in \mathcal{U}_{n,i}} g_{n,i,u,t}^{\mathrm{power}} - \sum_{n \in \mathcal{N}} \sum_{y \in \mathcal{Y}_{n,i}} g_{n,i,y,t}^{\mathrm{chp,p}}$$
$$- \sum_{n \in \mathcal{N}} \sum_{e \in \mathcal{E}} g_{n,i,t}^{e} = 0 \qquad (\delta_{i,t}^{\mathrm{power}}), \ \forall t \tag{2}$$

$$Q_{n,i,t}^{\mathrm{heat}} - \sum_{x \in \mathcal{X}_{n,i}} E_n^{\mathrm{trans}} g_{n,i,x,t}^{\mathrm{heat}} - \sum_{y \in \mathcal{Y}_{n,i}} E_n^{\mathrm{trans}} g_{n,i,y,t}^{\mathrm{chp,h}}$$
$$+ r_{n,i,t}^{\mathrm{in}} - r_{n,i,t}^{\mathrm{out}} = 0 \qquad (\delta_{n,i,t}^{\mathrm{heat}}), \ \forall n, t \tag{3}$$

$$g_{n,i,y^{\mathrm{B}},t}^{\mathrm{chp,p}} - R_{y^{\mathrm{B}}}^{\mathrm{p\text{-}t\text{-}h}} g_{n,i,y^{\mathrm{B}},t}^{\mathrm{chp,h}} = 0$$
$$(\phi_{n,i,y^{\mathrm{B}},t}^{\mathrm{B}}), \ \forall n, y^{\mathrm{B}} \in \mathcal{Y}^{\mathrm{B}}{}_{n,i}, t \tag{4}$$

$$R_{y^{\mathrm{E}}}^{\mathrm{p\text{-}t\text{-}h}} g_{n,i,y^{\mathrm{E}},t}^{\mathrm{chp,h}} - g_{n,i,y^{\mathrm{E}},t}^{\mathrm{chp,p}} \leq 0$$
$$(\phi_{n,i,y^{\mathrm{E}},t}^{\mathrm{E,p\text{-}t\text{-}h}}), \ \forall n, y^{\mathrm{E}} \in \mathcal{Y}^{\mathrm{E}}{}_{n,i}, t \tag{5}$$

$$R_{y^{\mathrm{E}}}^{\mathrm{f\text{-}t\text{-}h}} g_{n,i,y^{\mathrm{E}},t}^{\mathrm{chp,h}} + R_{y^{\mathrm{E}}}^{\mathrm{f\text{-}t\text{-}p}} g_{n,i,y^{\mathrm{E}},t}^{\mathrm{chp,p}} - \overline{F}_{y^{\mathrm{E}}} \leq 0$$
$$(\phi_{n,i,y^{\mathrm{E}},t}^{\mathrm{E,ub\text{-}fuel}}), \ \forall n, y^{\mathrm{E}} \in \mathcal{Y}^{\mathrm{E}}{}_{n,i}, t \tag{6}$$

$$R_{n,i}^{\mathrm{heat\text{-}only}} Q_{n,i,t}^{\mathrm{heat}} - \sum_{x \in \mathcal{X}_{n,i}} E_n^{\mathrm{trans}} g_{n,i,x,t}^{\mathrm{heat}} \leq 0$$
$$(\delta_{n,i,t}^{\mathrm{heat\text{-}only}}), \ \forall n, t \tag{7}$$

$$g_{n,i,u,t}^{\mathrm{power}} - T_t \overline{G}_{n,i,u}^{\mathrm{power}} \leq 0 \qquad (\lambda_{n,i,u,t}^{\mathrm{power}}), \ \forall n, u \in \mathcal{U}_{n,i}, t \tag{8}$$

$$g_{n,i,y,t}^{\mathrm{chp,h}} - T_t \overline{G}_{n,i,y}^{\mathrm{chp,h}} \leq 0 \qquad (\lambda_{n,i,y,t}^{\mathrm{chp,h}}), \ \forall n, y \in \mathcal{Y}_{n,i}, t \tag{9}$$

$$g_{n,i,x,t}^{\mathrm{heat}} - T_t \overline{G}_{n,i,x}^{\mathrm{heat}} \leq 0 \qquad (\lambda_{n,i,x,t}^{\mathrm{heat}}), \forall n, x \in \mathcal{X}_{n,i}, t \tag{10}$$

$$g_{n,i,t}^{e} - T_t A_{n,t}^{e} \overline{G}_{n,i}^{e} = 0 \qquad (\lambda_{n,i,t}^{e}), \ \forall n, e, t \tag{11}$$

$$g_{n,i,u,t}^{\mathrm{power}} - g_{n,i,u,t-1}^{\mathrm{power}} - T_t R_u^{\mathrm{power\text{-}up}} \overline{G}_{n,i,u}^{\mathrm{power}} \leq 0$$
$$(\rho_{n,i,u,t}^{\mathrm{power\text{-}up}}), \ \forall n, u \in \mathcal{U}_{n,i}, t \tag{12}$$

$$g_{n,i,u,t-1}^{\mathrm{power}} - g_{n,i,u,t}^{\mathrm{power}} - T_t R_u^{\mathrm{power\text{-}down}} \overline{G}_{n,i,u}^{\mathrm{power}} \leq 0$$
$$(\rho_{n,i,u,t}^{\mathrm{power\text{-}down}}), \ \forall n, u \in \mathcal{U}_{n,i}, t \tag{13}$$

$$g_{n,i,y,t}^{\mathrm{chp,h}} - g_{n,i,y,t-1}^{\mathrm{chp,h}} - T_t R_y^{\mathrm{chp\text{-}up}} \overline{G}_{n,i,y}^{\mathrm{chp,h}} \leq 0$$
$$(\rho_{n,i,y,t}^{\mathrm{chp\text{-}up}}), \ \forall n, y \in \mathcal{Y}_{n,i}, t \tag{14}$$

$$g_{n,i,y,t-1}^{\mathrm{chp,h}} - g_{n,i,y,t}^{\mathrm{chp,h}} - T_t R_y^{\mathrm{chp\text{-}down}} \overline{G}_{n,i,y}^{\mathrm{chp,h}} \leq 0$$
$$(\rho_{n,i,y,t}^{\mathrm{chp\text{-}down}}), \ \forall n, y \in \mathcal{Y}_{n,i}, t \tag{15}$$

$$g_{n,i,x,t}^{\text{heat}} - g_{n,i,x,t-1}^{\text{heat}} - T_t R_x^{\text{heat-up}} \overline{G}_{n,i,x}^{\text{heat}} \leq 0$$
$$(\rho_{n,i,x,t}^{\text{heat-up}}), \ \forall n, x \in \mathcal{X}_{n,i}, t \tag{16}$$

$$g_{n,i,x,t-1}^{\text{heat}} - g_{n,i,x,t}^{\text{heat}} - T_t R_x^{\text{heat-down}} \overline{G}_{n,i,x}^{\text{heat}} \leq 0$$
$$(\rho_{n,i,x,t}^{\text{heat-down}}), \ \forall n, x \in \mathcal{X}_{n,i}, t \tag{17}$$

$$r_{n,i,t}^{\text{sto}} - (1 - E^{\text{dec}})^{T_t} r_{n,i,t-1}^{\text{sto}} - E^{\text{eff}} r_{n,i,t}^{\text{in}} + r_{n,i,t}^{\text{out}} = 0$$
$$(\beta_{n,i,t}^{\text{bal}}), \ \forall n, t \tag{18}$$

$$r_{n,i,t}^{\text{in}} - T_t E^{\text{in}} \overline{E}_{n,i}^{\text{max}} \leq 0 \quad (\beta_{n,i,t}^{\text{in}}), \ \forall n, t \tag{19}$$

$$r_{n,i,t}^{\text{out}} - T_t E^{\text{out}} \overline{E}_{n,i}^{\text{max}} \leq 0 \quad (\beta_{n,i,t}^{\text{out}}), \ \forall n, t \tag{20}$$

$$\underline{E}_{n,i}^{\text{min}} \leq r_{n,i,t}^{\text{sto}} \leq \overline{E}_{n,i}^{\text{max}} \quad (\beta_{n,i,t}^{\text{lb}}, \beta_{n,i,t}^{\text{ub}}), \ \forall n, t \tag{21}$$

$$g_{n,i,u,t}^{\text{power}} \geq 0 \ \forall n, u \in \mathcal{U}_{n,i}, t; \ g_{n,i,y,t}^{\text{chp,p}}, g_{n,i,y,t}^{\text{chp,h}} \geq 0 \ \forall n,$$
$$y \in \mathcal{Y}_{n,i}, t; \ g_{n,i,x,t}^{\text{heat}} \geq 0 \ \forall n, x \in \mathcal{X}_{n,i}, t; \ g_{n,i,t}^{e}, q_{n,i,t}^{\text{power}},$$
$$r_{n,i,t}^{\text{sto}}, r_{n,i,t}^{\text{in}}, r_{n,i,t}^{\text{out}} \geq 0 \ \forall n, t \tag{22}$$

where $\Gamma := \{g_{n,i,u,t}^{\text{power}}, g_{n,i,y,t}^{\text{chp,p}}, g_{n,i,y,t}^{\text{chp,h}}, g_{n,i,x,t}^{\text{heat}}, g_{n,i,t}^{e}, q_{n,i,t}^{\text{power}}, r_{n,i,t}^{\text{sto}}, r_{n,i,t}^{\text{in}}, r_{n,i,t}^{\text{out}} : i \in \mathcal{I}, n \in \mathcal{N}, u \in \mathcal{U}_{n,i}, y \in \mathcal{Y}_{n,i}, x \in \mathcal{X}_{n,i}, e \in \mathcal{E}, t \in \mathcal{T}\}$. Dual variables are in brackets next to their corresponding constraints. Note that in (1), the CHP variable cost could be implemented as being quadratic in both power and heat output as in [14]. However, the purpose of such a function in [14] is to capture the increasing marginal cost of curtailing wind in a small network with two CHP plants, two conventional plants, and a wind farm. By contrast, we model the entire Nordic region with fourteen nodes and several GWs of installed capacity. Thus, even though the marginal cost of each type of CHP unit is constant, the diversity of CHP unit types and capacities (see Table II) leads to an upward-sloping supply stack, i.e., effectively an increasing marginal cost on aggregate. Constraints (2)-(3) ensure the balance between electricity/heat production and sales, respectively. Constraints (4)-(6) represent CHP operations: (4) sets the power-to-heat production ratio for back-pressure plants; (5)-(6) define the FOR for extraction plants. Constraint (7) guarantees a minimum share of nodal DH demand to be covered by heat-only. Constraints (8)-(11) limit production levels by the maximum capacities, and (12)-(17) set ramping limits for up and down ramping per total installed capacity. Constraints (18)-(21) limit heat storage operations: energy balance between time steps (18), charge rate (19), discharge rate (20), and maximum capacity (21).

2) Grid Owner: The grid owner controls power transmission to maximize profit (23) from congestion fees, $\omega_{n,t}$. As in [19], the nodal-balance constraint (29) is not part of the grid-owner's optimization. Instead, it is a market-clearing condition with its shadow prices used as congestion charges to guide the producers' and grid-owner's decisions. [19] shows that such a structure with arbitrage is equivalent to the model with a welfare-maximizing ISO that does have the nodal-balance constraint under its optimization [30]. Moreover, the link between the grid owner and the producers arises precisely because of the market-clearing condition (29): each decision maker takes the congestion rent, i.e., the dual variable associated with (29), as given when making its generation or flow decision. Our approach considers both AC and DC lines, i.e., DC load-flow linearization with DC links, as in [31]. Decision variables are

flow, $f_{\ell,t}$, for the whole grid, and voltage angle, $\theta_{n^{\text{AC}},t}$, for the AC part. $\mathcal{N}^{\text{AC}} \subset \mathcal{N}$ refers to nodes connected to an AC line, whereas nodes in $\mathcal{N}^{\text{DC}} \subset \mathcal{N}$ have only DC connections.

$$\min_{\theta_{n^{\text{AC}},t}, f_{\ell,t}} - \sum_{t \in \mathcal{T}} \sum_{n \in \mathcal{N}} \omega_{n,t} \sum_{\ell \in \mathcal{L}} M_{\ell,n} T_t f_{\ell,t} \tag{23}$$

$$\text{s.t.} \sum_{n^{\text{AC}} \in \mathcal{N}^{\text{AC}}} T_t H_{\ell^{\text{AC}},n^{\text{AC}}} \theta_{n^{\text{AC}},t} - T_t f_{\ell^{\text{AC}},t} = 0$$
$$(\eta_{\ell^{\text{AC}},t}), \ \forall \ell^{\text{AC}} \in \mathcal{L}^{\text{AC}}, t \tag{24}$$

$$T_t f_{\ell,t} - T_t \overline{K}_\ell \leq 0 \ (\overline{\mu}_{\ell,t}), \ \forall \ell, t \tag{25}$$

$$-T_t f_{\ell,t} - T_t \underline{K}_\ell \leq 0 \ (\underline{\mu}_{\ell,t}), \ \forall \ell, t \tag{26}$$

$$T_t S_{n^{\text{AC}}} \theta_{n^{\text{AC}},t} = 0 \ (\gamma_{n^{\text{AC}},t}), \ \forall n^{\text{AC}} \in \mathcal{N}^{\text{AC}}, t \tag{27}$$

$$\theta_{n^{\text{AC}},t} \text{ and } f_{\ell,t} \text{ u.r.s.}, \ \forall n^{\text{AC}} \in \mathcal{N}^{\text{AC}}, \ell, t \tag{28}$$

where u.r.s. denotes unrestricted in sign. Constraint (24) is the loop-flow constraint for the AC lines using a DC load-flow linearization based on Kirchhoff's current law in a circuit. Constraints (25) and (26) ensure that the maximum capacities of transmission lines $\ell \in \mathcal{L}$ are not exceeded. Constraint (27) sets the slack node for the DC load-flow in the AC circuit.

3) Market-Clearing Condition: To ensure that nodal production and exports/imports meet the demand, we use:

$$\sum_{i \in \mathcal{I}} q_{n,i,t}^{\text{power}} - \sum_{i \in \mathcal{I}} \sum_{u \in \mathcal{U}_{n,i}} g_{n,i,u,t}^{\text{power}} - \sum_{i \in \mathcal{I}} \sum_{y \in \mathcal{Y}_{n,i}} g_{n,i,y,t}^{\text{chp,p}}$$
$$- \sum_{i \in \mathcal{I}} \sum_{e \in \mathcal{E}} g_{n,i,t}^{e} - \sum_{\ell \in \mathcal{L}} T_t M_{\ell,n} f_{\ell,t} = 0 \quad (\omega_{n,t}, \text{ u.r.s.}), \ \forall n, t. \tag{29}$$

4) Equilibrium Problem: Because (1)-(22) and (23)-(28) are convex optimization problems, they can be replaced by their Karush-Kuhn-Tucker (KKT) conditions. Thus, the equilibrium problem comprising (1)-(22), (23)-(28), and (29) may be rendered as a mixed complementarity problem (MCP) comprising (F1)-(F30), (G1)-(G6), and (29) (in Appendix). Under a Cournot oligopoly, the producers assume that total demand, $\sum_{i' \in \mathcal{I}} q_{n,i',t}^{\text{power}}$, in their objective function (1) is not a constant, as under perfect competition, but affected by their decisions as reflected in KKT condition (F6).

III. NUMERICAL EXAMPLES

We use 2014 data to study four seasonal scenarios, (M) March, (J) June, (S) September, and (D) December, as representative 24 hours (monthly averages for reference demand, prices, and production) in two-hour time blocks.

A. Data

We implement numerical examples for the Nordic energy system (Fig. 2) comprising Nord Pool and national DH supply. Nord Pool prices are affected by regional deviations due to transmission congestion along with temperatures and hydrological conditions, which result in seasonal trends (Fig. 3 [32]). The price elasticity of demand is assumed to be -0.25 [33]. For modeling purposes, nodes $n9$-$n14$ are auxiliary; the rest correspond to countries, except for Denmark, which has two price areas. Furthermore, Baltic nodes have an aggregated producer and no DH consideration. The dashed lines in Fig.
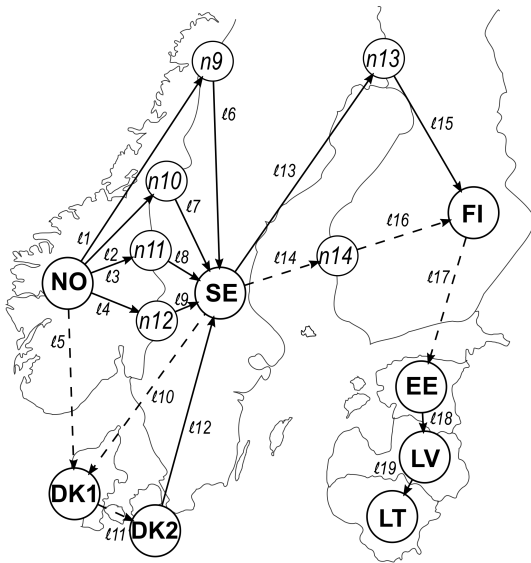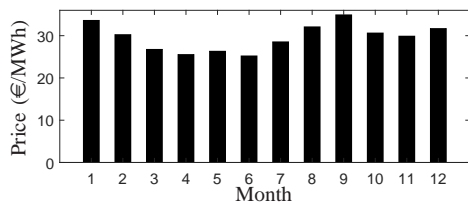
Fig. 2. Test network of the Nordic power system.

Fig. 3. Average Nord Pool system prices (€/MWh) in 2014.

TABLE I
LINE TYPES AND MAXIMUM THERMAL CAPACITIES (MW).

Line	Type	Positive direction	Negative direction
$\ell 1$	AC	650	450
$\ell 2$	AC	150	250
$\ell 3$	AC	600	1000
$\ell 4$	AC	2145	2095
$\ell 5$	DC	950	1000
$\ell 6$	AC	650	450
$\ell 7$	AC	150	250
$\ell 8$	AC	600	1000
$\ell 9$	AC	2145	2095
$\ell 10$	DC	680	740
$\ell 11$	DC	590	600
$\ell 12$	AC	1700	1300
$\ell 13$	AC	1480	1120
$\ell 14$	DC	1200	1200
$\ell 15$	AC	1480	1120
$\ell 16$	DC	1200	1200
$\ell 17$	DC	860	1016
$\ell 18$	AC	750	779
$\ell 19$	AC	1234	684

2 correspond to DC links and solid lines to the AC grid [34]; these are assumed to have similar conductivity characteristics. Maximum thermal line capacities (Table I) are based on the most frequent Elspot day-ahead capacities in 2014 [32].

Average DH prices (excluding taxes) in 2014 were €59/MWh$_{th}$ in Finland, €66/MWh$_{th}$ in Denmark, €70/MWh$_{th}$ in Norway, and €71/MWh$_{th}$ in Sweden [35]–[38]. To account for capacity centralization, we consider

TABLE II
MARGINAL COST ESTIMATES ($\mathcal{U}$ IN €/MWh, $\mathcal{X}$ IN €/MWh$_{th}$, $\mathcal{Y}$ IN €/MWH AND €/MWH$_{th}$). ("-" NOT APPLICABLE, *CALIBRATED, **HOUR-DEPENDENT)

Fuel	Types	$C_{n,u,t}^{\text{power}}$	$C_{y^B}^{\text{chp,p}}/C_{y^B}^{\text{chp,h}}$	$C_{y^E}^{\text{chp,p}}/C_{y^E}^{\text{chp,h}}$	C_x^{heat}
Coal	$u1, y1, x1$	29	-	15 / 30	47
Natural gas	$u2, y2, x2$	85	45 / 50	46 / 51	53
CCGT	$u3$	47,*	-	-	-
Oil	$u4, y4, x4$	78	37 / 51	38 / 52	54
Biomass	$u5, y5, x5$	62	-	28 / 26	27
Oil shale	$u6$	33	-	-	-
Nuclear	$u7$	9	-	-	-
Hydro	$u8$	*,**	-	-	-
Waste	$y9, x9$	-	-	25 / 3	24
Peat	$y10, x10$	-	-	22 / 25	25
Bio oil	$x11$	-	-	-	51

DH transmission efficiencies (Sweden 88%, Finland 91%, Denmark 80%, and Norway 89%) and set minimum shares of fringes' DH supplies to be covered by heat-only (Sweden 60%, Finland 30%, Denmark 27%, and Norway 99% as annual DH production not covered by CHP) [35], [37]–[43]. Producers' hourly DH sales are estimated based on their share of the annual supply and an estimated DH demand based on outside temperature (heating-degree hours) and hot-water demand (30% of annual DH demand).

Production costs (Table II) are based on fuel costs (power [44]–[46], heat [47], [48]) variable O&M costs [49], and CO_2 emission costs (€5/t, [2]) along with emission rates [50]. The CHP marginal cost is allocated to heat and power proportional to the energy content of each product, which is known as the energy method [51].

The producer set, $\mathcal{I}$, includes the largest Nordic power-only and CHP owners. The rest and the majority of DH producers are aggregated into national fringe groups.[2] Installed power and CHP capacities (Tables III and IV, respectively) are mainly from Platts [52] but updated from the companies' websites. Finnish heat-only capacity is from [35] (Table V). Where available, producer-level data for other countries are individually obtained from the companies' websites (Vattenfall, Statkraft). Others are estimated from companies' annual DH production mix, their relation to the Finnish DH production, and Finland's installed heat-only capacity. Power-to-heat ratios ($R_{y^{B/E}}^{\text{p-t-h}}$) for CHP operations are from [49]. For simplicity, we use $R_{y^E}^{\text{f-t-h}}$=0.25 and $R_{y^E}^{\text{f-t-p}}$=2.4 for all extraction unit types [10]. Maximum fuel intake ($\overline{F}_{y^E}$) is defined as the ratio between total capacity and total efficiency of an extraction unit y^E.

In 2014, there was roughly 50 GWh$_{th}$ of heat storage in Denmark [53] and 17 GWh$_{th}$ in Finland [54]. SE and NO capacities are estimated from Finnish data, resulting in ca. 25 GWh$_{th}$ and 4 GWh$_{th}$, respectively. The ownership structure is based on producers' DH capacities. We use 99% for input and hourly periodic storage efficiency. Charge and discharge rates, and minimum and initial states of charge, are set to 30%.

Hydropower availability represents historical monthly av-

TABLE III
INSTALLED POWER-ONLY CAPACITY (GW) IN 2014 AND AVAILABILITY
PERCENTAGES. (*AGGREGATED, INCL. POSSIBLE CHP-POWER)

Node	Producer	u1	u2	u3	u4	u5	u6	u7	u8	Wind	PV
SE	i1	-	-	-	-	-	-	3.2	8	0.4	-
	i2	-	0.1	0.3	0.3	0.1	-	-	2.6	0.2	-
	i3	-	-	-	-	-	-	3.7	-	-	-
	i4	-	-	-	-	-	-	2.6	-	-	-
	i5	-	-	-	-	-	-	-	2.9	-	-
	i6	0.1	0.1	0.1	1.8	0.1	-	-	3.9	4.8	0.1
FI	i5	0.6	-	-	-	-	-	1.0	0.8	-	-
	i7	-	-	-	-	-	-	1.8	-	-	-
	i8	0.5	-	-	0.2	-	-	-	0.4	-	-
	i9	-	-	-	0.1	-	-	-	-	-	-
	i10	-	-	-	-	-	-	-	1.1	-	-
	i11	-	0.1	-	1.1	-	-	-	0.8	0.6	-
DK1	i12	-	-	-	-	-	-	-	-	0.4	-
	i1	-	-	-	-	-	-	-	-	0.4	-
	i13	-	-	-	-	-	-	-	-	3.0	0.4
DK2	i12	-	-	-	0.7	-	-	-	-	0.2	-
	i13	-	-	-	-	-	-	-	-	0.8	0.2
NO	i14	-	-	0.2	-	-	-	-	9.9	0.2	-
	i15	-	-	-	-	-	-	-	2.5	-	-
	i16	-	-	-	-	-	-	-	2.0	-	-
	i17	-	-	-	-	-	-	-	1.8	-	-
	i18	-	-	-	-	-	-	-	1.7	-	-
	i19	-	-	-	-	-	-	-	1.4	-	-
	i20	-	-	-	-	-	-	-	1.2	-	-
	i21	-	-	0.2	0.1	-	-	-	9.6	0.7	-
EE*	i22	-	0.2	-	-	0.1	1.8	-	-	0.3	-
LV*	i22	-	0.5	-	-	-	-	-	1.5	0.1	-
LT*	i22	-	1.6	0.5	0.8	-	-	-	1.0	0.3	-
%	Available	90	95	80	86	95	90	90	Fig. 4c	Fig. 4a	Fig. 4b

TABLE IV
INSTALLED CHP-POWER CAPACITY (GW) IN 2014 AS BACK-PRESSURE
(y^B) AND EXTRACTION (y^E) UNITS AND RELATED PARAMETERS.

Node	Producer	$y1^E$	$y9^E$	$y2^B$	$y2^E$	$y4^B$	$y4^E$	$y10^E$	$y5^E$
SE	i1	-	-	-	-	-	-	-	0.2
	i2	-	-	-	-	0.1	-	-	0.2
	i5	0.1	0.1	-	-	-	0.2	-	0.2
	i6	0.2	0.2	0.1	0.1	0.1	0.4	-	1.8
FI	i5	0.1	-	0.3	-	-	-	0.1	-
	i9	0.4	-	0.6	-	-	-	-	-
	i11	0.9	-	0.7	0.2	-	0.1	1.1	0.5
DK1	i12	1.1	-	0.1	0.4	-	-	-	0.1
	i1	0.7	-	-	-	-	-	-	-
	i13	-	0.1	0.5	0.4	-	-	-	-
DK2	i12	1.1	-	-	0.3	-	-	-	0.5
	i13	0.3	0.1	0.1	0.3	-	0.1	-	0.1
%	Available	90	90	95	95	95	95	95	95
$R_{y^{B/E}}^{\text{p-t-h}}$		0.58	0.28	0.78	1.18	0.78	1.18	0.43	0.43

TABLE V
INSTALLED HEAT-ONLY CAPACITY (GW_{th}) IN 2014 AND AVAILABILITY
PERCENTAGES. (*ESTIMATES BASED ON FI)

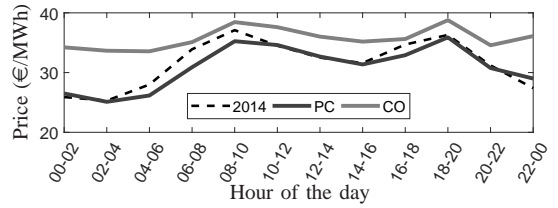| Node	Producer	x1	x9	x2	x4	x10	x5	x11
SE*	i1	-	-	-	-	-	0.5	-
	i2	-	0.3	0.1	-	-	0.2	-
	i5	0.2	0.4	-	-	-	0.2	0.1
	i6	0.6	6.4	0.6	0.6	0.8	12.2	0.6
FI	i5	0.2	-	0.6	0.4	-	-	-
	i9	0.2	-	1.0	1.2	-	-	-
	i11	-	-	2.3	5.3	0.9	1.3	-
DK1*	i13	1.7	1.7	1.5	0.1	-	2.9	-
DK2*	i13	1.1	1.1	1.0	0.1	-	1.9	-
NO*	i14	-	0.3	-	-	-	0.1	-
	i21	-	3.3	0.3	0.1	-	1.2	-
%	Available	90	90	95	95	95	95	95

Fig. 5. Average system prices under perfect competition (PC), Cournot oligopoly (CO), and historical 2014 prices in the (M) March scenario.

TABLE VI
TEST CASES.

Model	Perfect Competition	Cournot Oligopoly
CHP (status quo)	SQ-PC	SQ-CO
CHP decoupling	DE-PC	DE-CO

B. Calibration

To obtain credible results, the model is calibrated to produce close-to 2014 Nord Pool prices (Fig. 5, mainly between perfect competition and Cournot oligopoly) and a reasonable production mix. This is done by adjusting hydro water values and availability (Fig. 4c). In addition, the CCGT fuel price is set to €47/MWh to calibrate prices in the Baltic nodes.

C. Test Cases

We define four test cases (Table VI) to study our research questions. Thus, in addition to the market power consideration, we test two possibilities for CHP: the current situation and a hypothetical case in which the power and heat capacities are decoupled into power-only and heat-only components. In practice, this means the same nominal capacities implied by (6) and (9) without the linking constraints (4)–(5), while using the corresponding power-only and heat-only costs from Table II (except for waste and peat, for which there is no power-only, so we use power component costs equal to biomass).

Thus, combined with the seasonal scenarios (M), (J), (S), and (D), we implement 4x4 runs in the General Algebraic Modeling System (GAMS). We reformulate the MCPs as analogous convex quadratic programs (QPs) because the resulting optimization problems can be solved more quickly and reliably with CPLEX [58] than as MCPs with PATH, which uses a generalization of Newton's method to solve a square system of equations [59].[3] According to Theorem 4.4 in [20], the global optimum for the corresponding QP is also an equilibrium solution to the MCP.

Finally, as indicated in Section II-A1, we also check the *ex post* power output for operational plants to verify that most of them run at well above their minimum power output levels. For example, in March under perfect competition, CHP plants operate at more than 0% but less than 20% of the rated power capacity only 4% of the time (14 plant-period instances out of a possible 350 plant-period combinations). The results are similar for other months, power-only plants,

erage production of installed capacity for Finland [55] and Sweden [56]. Norwegian hydropower production is estimated as 96% of the NO price areas' Nord Pool Elspot sales volumes [32]. Likewise, the availability of wind (Fig. 4a) and solar PV (Fig. 4b) represent average hourly production [32], [55]–[57].

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[3]On a workstation with a 2.40 GHz Intel i5-6300 core processor and 8 GB of RAM, the QP reformulation decreases the computational time of each problem instance from tens of minutes to a few seconds.
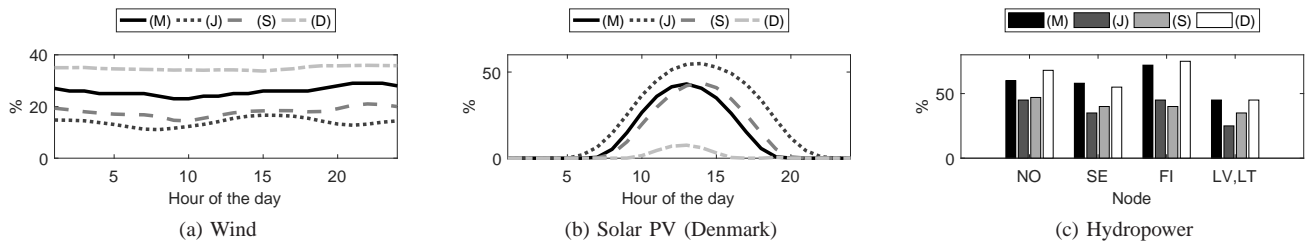
Fig. 4. Average hourly VRE production and available hydropower of installed capacity in 2014 in (M) March, (J) June, (S) September, and (D) December.
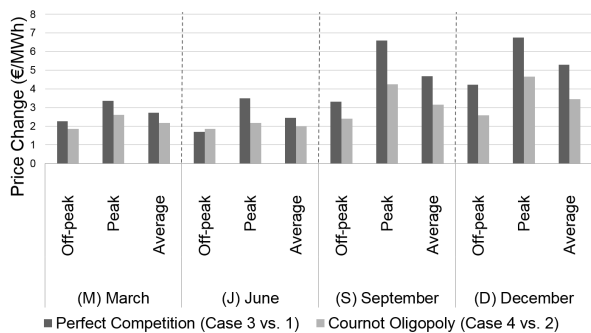

Fig. 6. CHP decoupling impacts on system average electricity prices.

TABLE VII
MARKET POWER IMPACT (Δ) ON SOCIAL WELFARE (SW), CONSUMER SURPLUS (CS), PRODUCER SURPLUS (PS), AND GRID OWNER'S SURPLUS (GR). VALUES IN THOUSANDS OF €, AVERAGE OF SEASONS (M)-(D).

	SQ-PC	SQ-CO	Δ	DE-PC	DE-CO	Δ
SW	87 113	86 777	- 336	84 549	84 237	- 312
CS	57 697	51 439	- 6 258	53 393	48 607	- 4 785
PS	28 578	34 686	6 107	30 136	34 805	4 670
GR	838	652	- 185	1 020	825	-196

Fig. 7. Market power impacts on system average electricity prices.

and Cournot oligopoly cases, i.e., the share of such minimum-power violations is between 1% and 4%.

D. Results

1) Power Markets: The decoupling of CHP production components increases electricity prices under perfect competition in all scenarios with a greater impact during peak hours (Fig. 6). The price increase indicates that CHP reduces system costs due to its higher joint production efficiency. Moreover, as extraction units comprise 83% of the CHP capacity in the Nordic energy system, there is also not much loss in flexibility due to cogeneration. Decoupling, thus, reduces cost effectiveness without offering any meaningful countervailing increase in flexibility. Decoupling impacts under Cournot oligopoly are similar to those under perfect competition, except for being smaller in magnitude perhaps because power output is already withheld due to market power. There is also more parity between off-peak and peak hours (Fig. 6).

Analysis of the impact of market power (Table VII) indicates that it decreases social welfare to the detriment of consumers but to the benefit of producers. Moreover, CHP enables this effect to be stronger. The effect of market power on prices (Fig. 7) is most severe during off-peak hours since there is more scope to increase prices. During peak hours, the impact of market power on prices is typically stronger with CHP (Cases SQ-PC and SQ-CO). To see this, note that more power is withheld during peak hours with CHP (Fig. 8) than without CHP (Fig. 9). Thus, on average, market power increases prices less when heat and power production are decoupled. In order to understand why less withholding may occur under decoupling, consider the profit-maximization problem of a monopolist with power-only generation: $\max_q P(q)q - C(q)$, which leads to the

first-order necessary condition $P'(q)q + P(q) - C'(q) = 0$. Because the three terms correspond to the marginal profit from an infinitesimal *increase* in production, we can unpick the effects of an infinitesimal *reduction* in sales: an increase in revenue due to a higher selling price, a decrease in revenue from lower sales, and a decrease in cost from less production. The first and third terms are marginal revenues from withholding, and the second term is the marginal cost of withholding. With CHP, the second term is reduced because the producer can offset the lost electricity market revenue with heat production. Hence, the availability of CHP reduces the marginal cost of withholding so that more power production is withheld.

2) DH Sector: CHP links the producers' ability to impact prices through power production decisions to the DH sector. Examining DH production, we find that market power increases (decreases) CHP (heat-only) output during season (D) (Fig. 10). The impact in other seasons is negligible and is significantly larger in (D) perhaps due to higher DH supply, i.e., more to withhold from. As indicated by Figs. 8 and 9 along with the preceding discussion, CHP makes it easier to withhold generation so that producers switch to CHP heat output from heat-only plants to meet their DH obligations. Indeed, somewhat paradoxically, by shutting down
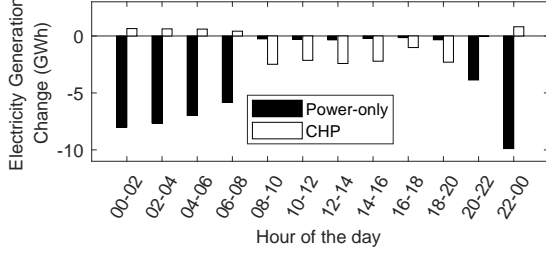
Fig. 8. Market power impacts on electricity output in (D) December (Case SQ-CO vs. SQ-PC).
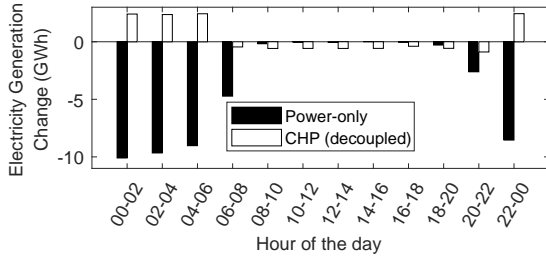

Fig. 9. Market power impacts on electricity output with CHP decoupling in (D) December (Case DE-CO vs. DE-PC).
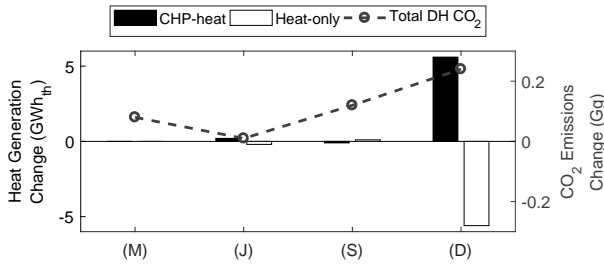

Fig. 10. Market power impacts on DH production (GWh$_{th}$) from CHP and heat-only, and on CO$_2$ emissions from the heating sector (Gg) (Case SQ-CO vs. SQ-PC).

heat-only plants rather than CHP units, producers behaving à la Cournot exert more leverage to increase power prices. Most of the power withholding comes from power-only, but a similar logic may apply for CHP during peak hours (Fig. 8). Finally, we find that market power slightly shifts production toward CHP biomass and peat in FI from heat-only biomass as producers seek to exert their market power, which increases CO$_2$ emissions as biomass is deemed carbon neutral in the EU's Emissions Trading System (ETS).

IV. DISCUSSION AND CONCLUSIONS

Transitions in energy markets affect the role of CHP in DH-intensive systems and call for suitable models for understanding what market outcomes there are when producers may behave strategically. In this paper, we investigate (i) whether CHP mitigates market power and (ii) how market power affects the DH sector's operations. To this end, we use complementarity modeling to compare perfect competition with a Cournot oligopoly for the Nordic region.

We find that (i) CHP can intensify producers' market power by reducing the opportunity cost of withholding output. We also observe that (ii) market power may shift DH production to CHP from heat-only because of the additional leverage it provides during peak hours. Finally, even with fixed DH sales, market power may impact CO$_2$ emissions from the DH sector due to production mix changes.

Our study provides insights into heat and power production interactions in the Nordic system, which has a significant DH sector. Such impacts should be taken into account when assessing the role of CHP in similar energy systems, even if our approach has been limited in considering more complex CHP operations and the topology of district heating. It may be that market power use is possible or attractive only for a small number of (CHP) producers. Finally, including VRE uncertainty and capacity expansion are fruitful topics for extending this research.

APPENDIX

From (1)–(12), the Cournot producers' KKT conditions are:

$$0 \le \left(C^{\text{power}}_{n,u,t} - \omega_{n,t} \right) - \delta^{\text{power}}_{i,t} + \lambda^{\text{power}}_{n,i,u,t} + \rho^{\text{power-up}}_{n,i,u,t} - \rho^{\text{power-up}}_{n,i,u,t+1}$$
$$+ \rho^{\text{power-down}}_{n,i,u,t+1} - \rho^{\text{power-down}}_{n,i,u,t} \perp g^{\text{power}}_{n,i,u,t} \ge 0, \ \forall n,i, u \in \mathcal{U}_{n,i}, t \quad \text{(F1)}$$

$$0 \le \left(C^{\text{chp,p}}_{y^{\text{B}}} - \omega_{n,t} \right) - \delta^{\text{power}}_{i,t} + \phi^{\text{B}}_{n,i,y^{\text{B}},t}$$
$$\perp g^{\text{chp,p}}_{n,i,y^{\text{B}},t} \ge 0, \ \forall n,i, y^{\text{B}} \in \mathcal{Y}^{\text{B}}_{n,i}, t \quad \text{(F2a)}$$

$$0 \le \left(C^{\text{chp,p}}_{y^{\text{E}}} - \omega_{n,t} \right) - \delta^{\text{power}}_{i,t} - \phi^{\text{E,p-t-h}}_{n,i,y^{\text{E}},t} + R^{\text{f-t-p}}_{y^{\text{E}}} \phi^{\text{E,ub-fuel}}_{n,i,y^{\text{E}},t}$$
$$\perp g^{\text{chp,p}}_{n,i,y^{\text{E}},t} \ge 0, \ \forall n,i, y^{\text{E}} \in \mathcal{Y}^{\text{E}}_{n,i}, t \quad \text{(F2b)}$$

$$0 \le C^{\text{chp,h}}_{y^{\text{B}}} - E^{\text{trans}}_n \delta^{\text{heat}}_{n,i,t} + \lambda^{\text{chp,h}}_{n,i,y^{\text{B}},t} - R^{\text{p-t-h}}_{y^{\text{B}}} \phi^{\text{B}}_{n,i,y^{\text{B}},t} + \rho^{\text{chp-up}}_{n,i,y^{\text{B}},t}$$
$$- \rho^{\text{chp-up}}_{n,i,y^{\text{B}},t+1} + \rho^{\text{chp-down}}_{n,i,y^{\text{B}},t+1} - \rho^{\text{chp-down}}_{n,i,y^{\text{B}},t}$$
$$\perp g^{\text{chp,h}}_{n,i,y^{\text{B}},t} \ge 0, \ \forall n,i, y^{\text{B}} \in \mathcal{Y}^{\text{B}}_{n,i}, t \quad \text{(F3a)}$$

$$0 \le C^{\text{chp,h}}_{y^{\text{E}}} - E^{\text{trans}}_n \delta^{\text{heat}}_{n,i,t} + \lambda^{\text{chp,h}}_{n,i,y^{\text{E}},t} + R^{\text{p-t-h}}_{y^{\text{E}}} \phi^{\text{E,p-t-h}}_{n,i,y^{\text{E}},t}$$
$$+ R^{\text{f-t-h}}_{y^{\text{E}}} \phi^{\text{E,ub-fuel}}_{n,i,y^{\text{E}},t} + \rho^{\text{chp-up}}_{n,i,y^{\text{E}},t} - \rho^{\text{chp-up}}_{n,i,y^{\text{E}},t+1} + \rho^{\text{chp-down}}_{n,i,y^{\text{E}},t+1} - \rho^{\text{chp-down}}_{n,i,y^{\text{E}},t}$$
$$\perp g^{\text{chp,h}}_{n,i,y^{\text{E}},t} \ge 0, \ \forall n,i, y^{\text{E}} \in \mathcal{Y}^{\text{E}}_{n,i}, t \quad \text{(F3b)}$$

$$0 \le C^{\text{heat}}_x - E^{\text{trans}}_n \delta^{\text{heat}}_{n,i,t} - E^{\text{trans}}_n \delta^{\text{heat-only}}_{n,i,t} + \lambda^{\text{heat}}_{n,i,x,t} + \rho^{\text{heat-up}}_{n,i,x,t}$$
$$- \rho^{\text{heat-up}}_{n,i,x,t+1} + \rho^{\text{heat-down}}_{n,i,x,t+1} - \rho^{\text{heat-down}}_{n,i,x,t}$$
$$\perp g^{\text{heat}}_{n,i,x,t} \ge 0, \ \forall n,i, x \in \mathcal{X}_{n,i}, t \quad \text{(F4)}$$

$$0 \le -\omega_{n,t} - \delta^{\text{power}}_{i,t} + \lambda^e_{n,i,t} \perp g^e_{n,i,t} \ge 0, \ \forall n,i,e,t \quad \text{(F5)}$$

$$0 \le -\left(D^{\text{int}}_{n,t} - D^{\text{slp}}_{n,t} \left(\sum_{i' \in \mathcal{I}} q^{\text{power}}_{n,i',t} + q^{\text{power}}_{n,i,t} \right) - \omega_{n,t} \right) + \delta^{\text{power}}_{i,t}$$
$$\perp q^{\text{power}}_{n,i,t} \ge 0, \ \forall n,i,t \quad \text{(F6)}$$

$$0 \le \beta^{\text{bal}}_{n,i,t} - (1 - E^{\text{dec}})^{T_t} \beta^{\text{bal}}_{n,i,t+1} + \beta^{\text{ub}}_{n,i,t} - \beta^{\text{lb}}_{n,i,t}$$
$$\perp r^{\text{sto}}_{n,i,t} \ge 0, \ \forall n,i,t \quad \text{(F7)}$$

$$0 \le \delta^{\text{heat}}_{n,i,t} - E^{\text{eff}} \beta^{\text{bal}}_{n,i,t} + \beta^{\text{in}}_{n,i,t} \perp r^{\text{in}}_{n,i,t} \ge 0, \ \forall n,i,t \quad \text{(F8)}$$

$$0 \le -\delta^{\text{heat}}_{n,i,t} + \beta^{\text{bal}}_{n,i,t} + \beta^{\text{out}}_{n,i,t} \perp r^{\text{out}}_{n,i,t} \ge 0, \ \forall n,i,t \quad \text{(F9)}$$

$$0 = \sum_{n \in \mathcal{N}} q^{\text{power}}_{n,i,t} - \sum_{n \in \mathcal{N}} \sum_{u \in \mathcal{U}_{n,i}} g^{\text{power}}_{n,i,u,t} - \sum_{n \in \mathcal{N}} \sum_{y \in \mathcal{Y}_{n,i}} g^{\text{chp,p}}_{n,i,y,t}$$
$$- \sum_{n \in \mathcal{N}} \sum_{e \in \mathcal{E}} g^e_{n,i,t} \quad \text{with } \delta^{\text{power}}_{i,t} \text{ u.r.s., } \forall i,t \quad \text{(F10)}$$

$$0 = Q^{\text{heat}}_{n,i,t} - \sum_{x \in \mathcal{X}_{n,i}} E^{\text{trans}}_n g^{\text{heat}}_{n,i,x,t} - \sum_{y \in \mathcal{Y}_{n,i}} E^{\text{trans}}_n g^{\text{chp,h}}_{n,i,y,t}$$
$$+ r^{\text{in}}_{n,i,t} - r^{\text{out}}_{n,i,t} \quad \text{with } \delta^{\text{heat}}_{n,i,t} \text{ u.r.s., } \forall n,i,t \quad \text{(F11)}$$

$$0 = g^{\text{chp,p}}_{n,i,y^{\text{B}},t} - R^{\text{p-t-h}}_{y^{\text{B}}} g^{\text{chp,h}}_{n,i,y^{\text{B}},t}$$
$$\text{with } \phi^{\text{B}}_{n,i,y^{\text{B}},t} \text{ u.r.s., } \forall n,i, y^{\text{B}} \in \mathcal{Y}^{\text{B}}_{n,i}, t \quad \text{(F12)}$$

$$0 \le g^{\text{chp,p}}_{n,i,y^{\text{E}},t} - R^{\text{p-t-h}}_{y^{\text{E}}} g^{\text{chp,h}}_{n,i,y^{\text{E}},t}$$
$$\perp \phi^{\text{E,p-t-h}}_{n,i,y^{\text{E}},t} \ge 0, \ \forall n,i,y^{\text{E}} \in \mathcal{Y}^{\text{E}}_{n,i}, t \tag{F13}$$

$$0 \le \overline{F}_{y^{\text{E}}} - R^{\text{f-t-h}}_{y^{\text{E}}} g^{\text{chp,h}}_{n,i,y^{\text{E}},t} - R^{\text{f-t-p}}_{y^{\text{E}}} g^{\text{chp,p}}_{n,i,y^{\text{E}},t}$$
$$\perp \phi^{\text{E,ub-fuel}}_{n,i,y^{\text{E}},t} \ge 0, \ \forall n,i,y^{\text{E}} \in \mathcal{Y}^{\text{E}}_{n,i}, t \tag{F14}$$

$$0 \le \sum_{x \in \mathcal{X}_{n,i}} E^{\text{trans}}_n g^{\text{heat}}_{n,i,x,t} - R^{\text{heat-only}}_{n,i} Q^{\text{heat}}_{n,i,t}$$
$$\perp \delta^{\text{heat-only}}_{n,i,t} \ge 0, \ \forall n,i,t \tag{F15}$$

$$0 \le T_t \overline{G}^{\text{power}}_{n,i,u} - g^{\text{power}}_{n,i,u,t} \quad \perp \lambda^{\text{power}}_{n,i,u,t} \ge 0, \ \forall n,i,u \in \mathcal{U}_{n,i}, t \tag{F16}$$

$$0 \le T_t \overline{G}^{\text{chp,h}}_{n,i,y} - g^{\text{chp,h}}_{n,i,y,t} \quad \perp \lambda^{\text{chp,h}}_{n,i,y,t} \ge 0, \ \forall n,i,y \in \mathcal{Y}_{n,i}, t \tag{F17}$$

$$0 \le T_t \overline{G}^{\text{heat}}_{n,i,x} - g^{\text{heat}}_{n,i,x,t} \quad \perp \lambda^{\text{heat}}_{n,i,x,t} \ge 0, \ \forall n,i,x \in \mathcal{X}_{n,i}, t \tag{F18}$$

$$0 = g^{e}_{n,i,t} - T_t A^{e}_{n,t} \overline{G}^{e}_{n,i} \quad \text{with } \lambda^{e}_{n,i,t} \text{ u.r.s., } \forall n,i,e,t \tag{F19}$$

$$0 \le -g^{\text{power}}_{n,i,u,t} + g^{\text{power}}_{n,i,u,t-1} + T_t R^{\text{power-up}}_u \overline{G}^{\text{power}}_{n,i,u}$$
$$\perp \rho^{\text{power-up}}_{n,i,u,t}, \ \forall n,i,u \in \mathcal{U}_{n,i}, t \tag{F20}$$

$$0 \le -g^{\text{power}}_{n,i,u,t-1} + g^{\text{power}}_{n,i,u,t} + T_t R^{\text{power-down}}_u \overline{G}^{\text{power}}_{n,i,u}$$
$$\perp \rho^{\text{power-down}}_{n,i,u,t}, \ \forall n,i,u \in \mathcal{U}_{n,i}, t \tag{F21}$$

$$0 \le -g^{\text{chp,h}}_{n,i,y,t} + g^{\text{chp,h}}_{n,i,y,t-1} + T_t R^{\text{chp-up}}_y \overline{G}^{\text{chp,h}}_{n,i,y}$$
$$\perp \rho^{\text{chp-up}}_{n,i,y,t}, \ \forall n,i,y \in \mathcal{Y}_{n,i}, t \tag{F22}$$

$$0 \le -g^{\text{chp,h}}_{n,i,y,t-1} + g^{\text{chp,h}}_{n,i,y,t} + T_t R^{\text{chp-down}}_y \overline{G}^{\text{chp,h}}_{n,i,y}$$
$$\perp \rho^{\text{chp-down}}_{n,i,y,t}, \ \forall n,i,y \in \mathcal{Y}_{n,i}, t \tag{F23}$$

$$0 \le -g^{\text{heat}}_{n,i,x,t} + g^{\text{heat}}_{n,i,x,t-1} + T_t R^{\text{heat-up}}_x \overline{G}^{\text{heat}}_{n,i,x}$$
$$\perp \rho^{\text{heat-up}}_{n,i,x,t}, \ \forall n,i,x \in \mathcal{X}_{n,i}, t \tag{F24}$$

$$0 \le -g^{\text{heat}}_{n,i,x,t-1} + g^{\text{heat}}_{n,i,x,t} + T_t R^{\text{heat-down}}_x \overline{G}^{\text{heat}}_{n,i,x}$$
$$\perp \rho^{\text{heat-down}}_{n,i,x,t}, \ \forall n,i,x \in \mathcal{X}_{n,i}, t \tag{F25}$$

$$0 = r^{\text{sto}}_{n,i,t} - (1 - E^{\text{dec}})^{T_t} r^{\text{sto}}_{n,i,t-1} - E^{\text{eff}} r^{\text{in}}_{n,i,t} + r^{\text{out}}_{n,i,t}$$
$$\text{with } \beta^{\text{bal}}_{n,i,t} \text{ u.r.s., } \forall n,i,t \tag{F26}$$

$$0 \le T_t E^{\text{in}} \overline{E}^{\text{max}}_{n,i} - r^{\text{in}}_{n,i,t} \quad \perp \beta^{\text{in}}_{n,i,t} \ge 0, \ \forall n,i,t \tag{F27}$$

$$0 \le T_t E^{\text{out}} \overline{E}^{\text{max}}_{n,i} - r^{\text{out}}_{n,i,t} \quad \perp \beta^{\text{out}}_{n,i,t} \ge 0, \ \forall n,i,t \tag{F28}$$

$$0 \le \overline{E}^{\text{max}}_{n,i} - r^{\text{sto}}_{n,i,t} \quad \perp \beta^{\text{ub}}_{n,i,t} \ge 0, \ \forall n,i,t \tag{F29}$$

$$0 \le -\underline{E}^{\text{min}}_{n,i} + r^{\text{sto}}_{n,i,t} \quad \perp \beta^{\text{lb}}_{n,i,t} \ge 0, \ \forall n,i,t \tag{F30}$$

From (23)–(28), the grid owner's KKT conditions are:

$$0 = \sum_{\ell^{\text{AC}} \in \mathcal{L}^{\text{AC}}} T_t H_{\ell^{\text{AC}},n^{\text{AC}}} \eta_{\ell^{\text{AC}},t} + T_t S_{n^{\text{AC}}} \gamma_{n^{\text{AC}},t}$$
$$\text{with } \theta_{n^{\text{AC}},t} \text{ u.r.s., } \forall n^{\text{AC}} \in \mathcal{N}^{\text{AC}}, t \tag{G1}$$

$$0 = -\sum_{n' \in \mathcal{N}} T_t M_{\ell,n'} \omega_{n',t} - T_t \eta_{\ell^{\text{AC}},t} + T_t \overline{\mu}_{\ell,t} - T_t \underline{\mu}_{\ell,t}$$
$$\text{with } f_{\ell,t} \text{ u.r.s., } \forall \ell, t \tag{G2}$$

$$0 = \sum_{n \in \mathcal{N}} T_t H_{\ell^{\text{AC}},n^{\text{AC}}} \theta_{n^{\text{AC}},t} - T_t f_{\ell^{\text{AC}},t}$$
$$\text{with } \eta_{\ell^{\text{AC}},t} \text{ u.r.s., } \forall \ell^{\text{AC}} \in \mathcal{L}^{\text{AC}}, t \tag{G3}$$

$$0 \le T_t \overline{K}_\ell - T_t f_{\ell,t} \quad \perp \overline{\mu}_{\ell,t} \ge 0, \ \forall \ell, t \tag{G4}$$

$$0 \le T_t \underline{K}_\ell + T_t f_{\ell,t} \quad \perp \underline{\mu}_{\ell,t} \ge 0, \ \forall \ell, t \tag{G5}$$

$$0 = T_t S_{n^{\text{AC}}} \theta_{n^{\text{AC}},t} \quad \text{with } \gamma_{n^{\text{AC}},t} \text{ u.r.s., } \forall n^{\text{AC}} \in \mathcal{N}^{\text{AC}}, t \tag{G6}$$

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