OPTIMIZATION OF A REGIONAL ENERGY SYSTEM

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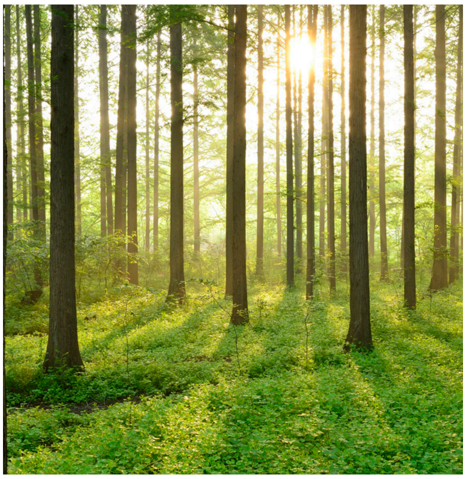
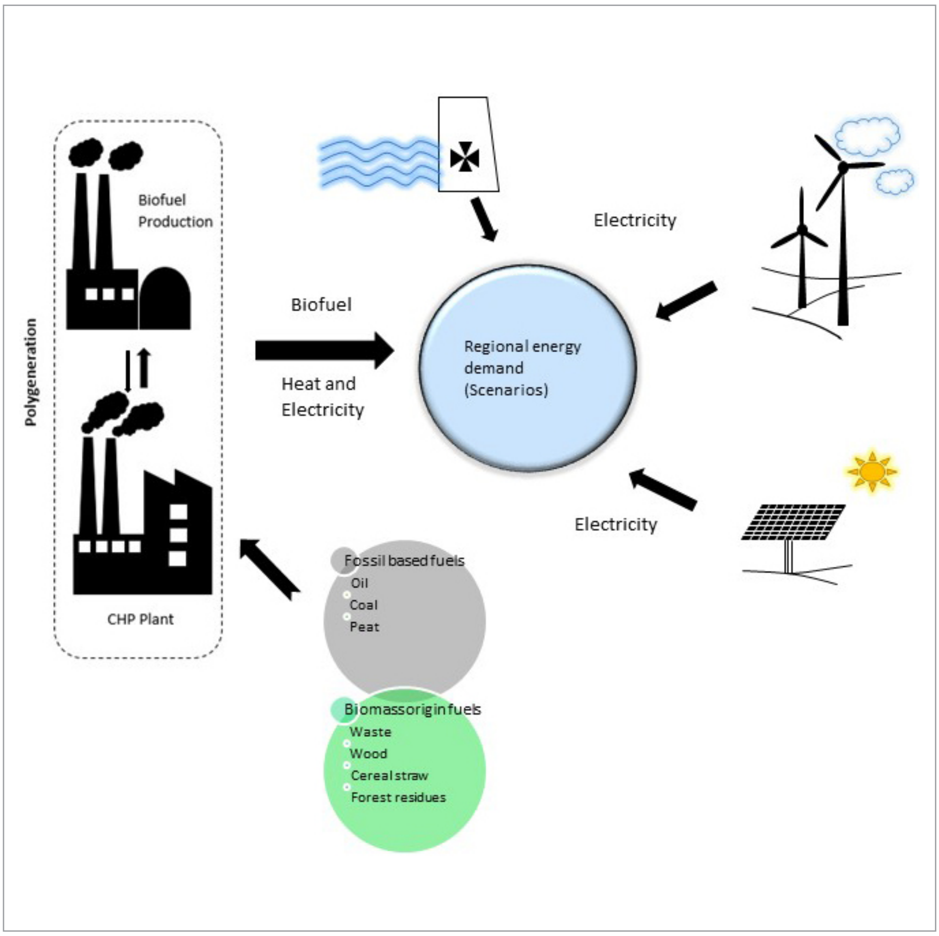


BRÄNSLEBASERAD EL- OCH VÄRMEPRODUKTION



Energiforsk

Optimization of a regional energy system

A study on production planning of CHP plants integrated with bioethanol production and local renewables

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Foreword

Denna rapport är slutrapportering av projekt P43434 SYDPOL – Systemutveckling för produktionsplanering och optimal drift av kraftverk (Energimyndighetens projektnummer P43434) inom SEBRA, samverkansprogrammet för bränslebaserad el- och värmeproduktion.

Programmets övergripande mål är att bidra till långsiktig utveckling av effektiva miljövänliga energisystemlösningar. Syftet är att medverka till framtagning av flexibla bränslebaserade anläggningar som kan anpassas till framtida behov och krav. Programmet är indelat i fyra teknikområden: anläggnings- och förbränningsteknik, processtyrning, material- och kemiteknik samt systemteknik. Programmet är en samverkan mellan Energiforsk och Energimyndigheten. Ingående projekt finansieras alltså av Energimyndigheten och av de parter som Energiforsk samlar i programmet.

Detta projekt har haft som syfte att utveckla en systemoptimeringsmodell med integration av förnybara energikällor och testa modellen på ett antal scenarier i Västmanland and Södermanland. Projektet har utförts av Mälardalens högskola med Eva Thorin som huvudprojektledare.

Projektet har följts av en referensgrupp bestående av:
Per Eriksson, Göteborg energi,
Nader Padban, Vattenfall,
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Sammanfattning

Många studier har utförts för optimering av produktionsplanering av kraftvärmeverk, framförallt utifrån ett marknadsperspektiv. Det är dock få studier som rör optimering av större system, som regioner, med integrering av förnybara energikällor. Denna studie handlar om optimering av ett regionalt energisystem med kraftvärmeverk och användning av förnybara energikällor. För att ta hänsyn till en ökad användning av mer förnybar energi som sol, vattenkraft och vind samt ökad användning av bioenergi behöver ett mer komplext system studeras för att optimera driften av kraftvärmeverk. Utvecklingen av de mer komplexa energisystemen beror av flera olika parametrar som tillgänglighet av olika resurser, energibehov och mönster för energianvändning samt priser för olika energiprodukter.

Elproduktionen från kraftvärmeverken beror av värmebehovet. Det betyder att under årets kalla dagar ökar inte bara värmeproduktionen utan även elproduktionen från kraftvärmeverken i ett energisystem. Det motsatta händer under sommaren då värmebehovet sjunker. På sommaren kan istället förnybara energikällor i systemet, som vindkraft, solenergi och vattenkraft, bidra med elproduktion. Då det finns en drivkraft att öka användningen av förnybara energikällor, för att minska miljöpåverkan, behövs en utveckling av mer komplexa energisystem med både användning av mer biomassa och avfall i kraftvärmeverk och utnyttjande av vindkraft, solenergi och vattenkraft.

En transportsektor oberoende av fossila bränslen är ett mål som ska uppnås till 2030 och ett sätt att göra det kan vara att både öka bioenergibaserade transportbränslen och öka användningen av eldrivna fordon och hybridfordon. Det innebär att fossilbaserade bränslen som bensin och diesel ersätts med biobränslen som t ex etanol och metanol, samt el. Därför kan integration av transportbränsleproduktion med kraftvärme vara en både kostnadseffektiv och energioptimal lösning.

Studiens mål har varit att utveckla en modell för simulering och optimering av kostnadseffektiv produktion och låga CO_2 utsläpp och att ge kunskap för produktionsplanering och driftstrategier för kraftvärmeverk i energisystemet. Polygenerering, ökad integration av förnybara energikällor, bränsle- och elpriser, framtida trender för energibehov och komplexa samband mellan olika parametrar ger nya dimensioner till optimering av energisystem. Simuleringsverktyg kan ge en bättre förståelse för dessa samband. Målet med denna studie har sin utgångspunkt från denna nya situation för energisystem med ökad integrering av förnybara energikällor och har varit följande:

1. Utveckla en systemmodell för optimering av värmekraftverk och ökad kunskap om produktionsplanering och drift strategier. Modellen omfattar hela kedjan från tillförsel av bränsle till energianvändning hos kund och även integration av produktion av transportbränslen och interaktion med regional vind, sol och vattenkraft.
2. Undersöka möjligheten att förbättra energitillförseln genom polygenerering på regional nivå.

3. Undersöka påverkan av ökad användning av tillgängliga förnybara energikällor i ett regionalt energisystem och transportsystem.
4. Ge rekommendationer för produktionsplanering i ett energisystem för energibolag.

I detta projekt har en optimeringsmodell utvecklats för undersökning av effekten av nyckelfaktorer där hela kedjan i energisystemet från inkommande bränsle till omvandlingsprocessen och energiprodukterna beaktas. Systemet som har undersökts består av regionala kraftvärmeverk med integration av produktion av transportbränsle, polygenerering, och interaktion med lokala förnybara resurser som vindkraft, vattenkraft och solenergi. Energisystemen i Västmanland och Södermanland har använts som fallstudier för utveckling av modellen. Då biomassabaserade energikällor ökar i energitillförseln och denna typ av resurs många gånger har låg densitet är det av stor vikt att undersöka energisystem på regional nivå och uppskatta potentialen för energitillförseln under regionala förhållanden

Regionala modeller har tidigare mest använts för att hitta lämplig placering av ny produktion medan detta projekt har fokuserat på stöd för produktionsplanering kopplat till drift av kraftvärmeverk i ett energisystem. Påverkan av driftstrategier på användningen av bränsle och CO_2 utsläpp har undersökts.

De regionala energisystemen har modellerats och följande optimeringsfall har undersökts:

- Ökad solelproduktion genom installation av nätkopplade solceller på taken till byggnaderna i regionen.
- Ökad användning av värmepumpar i systemet för att tillgodose delar av värmebehovet i fastigheterna.
- Integration av bioetanolproduktion, med halm från spannmålsodling i regionen, i befintliga kraftvärmeverk.
- Ökad användning av elektriska fordon, biobränslefordon och hybridfordon i det regionala transportsystemet.

Den metod som använts kan delas upp i tre delar; datainsamling och databehandling, konfigurering av systemet, samt modellering och optimering av fallstudierna.

- Datainsamling: data som behövs för modelleringen av ett regionalt energisystem samlas in. Tillgängliga databaser och offentliga uppgifter har använts och data har sedan bearbetats för de två fallstudierna, Västmanland och Södermanland.
- Systemkonfiguration: här identifieras systemets olika delar som typ av bränsle, omvandlingsprocesser, energiprodukter etc. och hur de ska inkluderas i optimeringsmodellen.
- Modellering och optimering: modellering, simulering och optimering av de regionala energisystemen med kraftvärmeverk integrerade med bioetanolproduktion, användning av regionala förnybara energikällor (vind-, sol- och vattenkraft) gjordes med hjälp av utveckling en MILP (Mixed Integer Linear Programming) modell i modelleringsverktyget GAMS (General

Algebraic Modelling System). De olika optimeringsfallen beskrivna ovan har tillämpats på de två regionerna Västmanland och Södermanland.

Västmanland består av tio kommuner med en total befolkning på 271 000 personer år 2015 och en landareal på 5 118 km^2. Energisystemet består av 34 energiverk med kraftvärmeverk och hetvattenpannor, 30 vattenkraftverk med en toppeffekt på ca 51 MW, en solcellspark med 90 solpaneler med en total kapacitet på 1 MW. De fem kraftvärmeverken i systemet producerar ca 250 GWh el och 1579 GWh värme per år. Huvudbränslet för verken är biomassebaserade bränslen med en liten del fossila bränslen, som olja och torv, som huvudsakligen används i hetvattenpannorna.

Södermanland består av nio kommuner med en befolkning på 291 340 personer 2015 och en total landareal på 6 075 km^2 . Det finns 22 energiverk där fyra är kraftvärmeverk och resten är värmeverk. Träbaserad biomassa är det huvudsakliga bränslet men fossil olja används också i några värmeverk. Det finns 18 vattenkraftverk med en toppeffekt på ca 9,5 MW och två solcellsparker. Den största av de två solcellparkerna producerar ca 1GWh per år. Det finns också nio vindkraftverk med en total kapacitet på 7 MW i Södermanland.

Datainsamlingen kan delas in i tre delar med data för energianläggningarna i regionen, data för de förnybara energikällorna samt data för transportsystemet. I data för energisystemet ingår vilka bränslen som används, mängden av tillgängliga och importerade bränslen, kostnader för bränslena, bränslenas omvandlingsfaktor till olika energiprodukter och omvandlingskostnad, produktionskapaciteten för varje anläggning, och de olika energiprodukternas pris. De bränslen som används i de studerade regionerna är olja (fossil och biobaserad), kol, torv, flis, avfall, träpellets, och biogas. Energitillförseln från respektive anläggning begränsas av tillgänglig biomassa och energigrödor, maximal produktion i anläggningen och det regionala behovet av värme, el och transportbränsle. CO_2 utsläppen från omvandlingen av bränslet till energiprodukten ingår också. Marginalutsläppen från importerade energiprodukter studeras också.

Data för förnybara energikällor omfattar elproduktionen från befintliga vattenkraftverk, solparker och vindkraftverk. I studien har också potentialen för solelsproduktion från solpaneler på byggnader i regionen studerats. För att kunna uppskatta denna potential behövs data för antal byggnader och tillgänglig yta för installation av solceller, solinstrålning och väderförhållanden, samt panelernas verkningsgrad.

För det regionala transportsystemet behövs data för totala antalet fordon som används i transportsystemet, typ av fordon, fordonsbränsle som används, sträckor som körs av varje fordon, samt bränslenas energiinnehåll. Data för tillgänglig mängd halm från spannmålen vete, havre, råg och korn behövs för uppskattning av bioetanolproduktion. För det används landareal och produktiviteten för spannmålsodling i regionen samt förhållandet mellan producerad halm och spannmål. Andelen halm som behöver plöjas ned för att undvika utarmning av jordarna har också inkluderats.

I den databearbetning som varit nödvändig ingår att omvandla data som anges per år eller per månad till värden per dag. Detta har gjorts genom att utgå från verkliga data för t ex en stad och skala upp samma mönster över året eller månaden för hela regionen. I vissa fall har data för andra år än det studerade året använts för att göra extrapoleringar till det studerade året. Potentialen för solelsproduktion från solpaneler på regionens byggnader har beräknats baserat på statistik om antal byggnader, typ av byggnader och deras ytor för att uppskatta totala ytan för solcellsinstallationer på regionens byggnader. För flerfamiljshus har takytan uppskattats baserat på statistik om lägenhetsytor och antagandet att varje våning har tre lägenheter. Vidare har bränslebehovet för transportsystemet i regionen uppskattats utifrån statistik om antal och typ av fordon, medelsträcka som varje typ av fordon körs, medelvärde för bränsleförbrukning och bränslets energiinnehåll, baserat på en metod som tidigare beskrivits i litteraturen.

Modellen av energisystemet innehåller en energibalans för varje kraftvärmeverk i regionen där även möjligheten till export av värme och el finns med. Samma verkningsgrad används för alla kraftvärmeverk och är baserad på data från ett verkligt verk. Produktionen för varje anläggning begränsas av dess maximala kapacitet. Behovet av värme och el beskrivs också med en energibalans i modellen. Möjligheten till import och användning av spillvärme från industri i regionen finns med i modellen. Produktion från värmeverk, vattenkraftverk, befintliga solparker och vindkraftverk samt produktion från solpaneler installerade på tillgängliga takytor på regionens byggnader finns också med i modellen. Systemet optimeras utifrån minimering av systemets kostnader.

5 olika scenarier, där det första är utgångsscenariot, har simulerats och optimerats för de två olika regionerna:

- Basscenario (S0- Energisystem): det regionala energisystemet år 2015 som inkluderar kraftvärmeverk, värmeverk, befintliga vattenkraftverk, vindkraftverk och solcellpark och också möjlig solelsproduktion från solceller installerade på taken på regionens byggnader.
- Scenario S1- Energisystem: ökad användning av värmepumpar som huvudsaklig värmekälla i byggnader, där fjärrvärmen var värmekällan tidigare, med en ökning på 10, 20 respektive 30%.
- Scenario S2- Energisystem: ökad användning av elfordon i regionen med en ökning på 10, 50 respektive 100%.
- Scenario S3- Polygenerering: bioetanolfordon i det regionala transportsystemet där etanolbehovet täcks med hjälp av integrerad etanolproduktion i kraftvärmeverk.
- Scenario S4- Polygenerering: användning av hybridfordon i det regionala transportsystemet, fordon som använder både el och bioetanol som bränsle.

Simuleringen av scenario S0, basscenariot, visar att solceller på regionens tak bidrar till att elproduktionen under sommaren överskrider behovet och el exporteras. I detta scenario står kraftvärmeverken i Västmanland för 19% av elbehovet i regionen medan 38% kan täckas av solelsproduktion och 35% av behovet täcks genom import till regionen, med en högre andel av import under vintern.

Ökad användning av värmepumpar, som ersättning för fjärrvärmen, påverkar kraftvärmeverkens bränsleanvändning och importen av el. Ökad värmeproduktion med värmepumpar i fastigheter minskar behovet av fjärrvärme och drifttiden, såväl som bränsleanvändningen, för kraftvärmeverken minskar. Då värmepumpar drivs av el ökar elbehovet och elimporten till systemet ökar. Resultaten för scenario S1 visar att en ökad användning av värmepumpar leder till en totalt sett mindre elproduktion från kraftvärmeverken och en ökad elimport till regionen. Detta kan vara en riskfaktor då elimporten närmar sig kapacitetsgränsen.

En ökad användning av elfordon i regionen, som simuleras i scenario 2, påverkar inte driftplaneringen av kraftvärmeverken nämnvärt och den totala elproduktionen från kraftvärmeverken är den samma i Västmanland medan den ändå ökar något, upp till ca 2%, i Södermanland. Elimporten ökar dock även i detta fall. I Västmanland är påverkan lägre än för scenario S1 med ökad användning av värmepumpar men i Södermanland hittar man fallet med högst elimport bland fallen för S3 med fler elfordon i regionen. I scenario S1, med ökad användning av värmepumpar, kan solelsproduktion bidra med upp till 45% av elbehovet i Västmanland och upp till 30% i Södermanland.

Scenario S3 och S4 har undersökts för Västmanland där energivärdet av halm från den regionala produktionen av spannmål uppskattas till ca 950 GWh. På grund av verkningsgraden för omvandlingsprocessen till bioetanol kan endast 28% av denna energimängd omsättas till bioetanol.

Resultaten av optimering av systemet med polygenerering enligt scenario 3, där regionens fordon antas drivas med etanol producerat integrerat i kraftvärmeproduktion, visar att den tillgängliga mängden halm i regionen inte är tillräcklig för att täcka etanolbehovet. För att täcka etanolbehovet behöver antingen halm eller bioetanol importeras till regionen. Resultatet av optimeringen visar att det är mer kostnadseffektivt att importera halm. Kostnaden för att importera bioetanol är 8 gånger högre jämfört med att importera halm. Mängden halm från regionen skulle kunna öka genom ökad produktion av grödor på tillgänglig mark i träda. Enligt Jordbruksverket ligger ca 13% av den totala odlingsbara marken i Västmanland i träda. Genom att använda denna mark för odling av spannmål skulle tillförseln av bioetanol kunna ökas med 23%, vilket fortfarande dock inte skulle vara tillräckligt för att täcka behovet enligt scenario 3. Andra typer av biobränslen kan användas inom transportsektorn. I Västmanland drivs ca 34% av bussarna med biogas, vilket motsvarar ca 4% av bioetanolbehovet enligt scenario 3. Verkningsgraden för det integrerade systemet är högre än för fristående bioetanolproduktion och kraftvärmeverk. Integrering av bioetanolproduktion med existerande kraftvärmeverk kan öka produktionen av värme och el.

Systemet i scenario 4 är en kombination av systemen i scenario 2 och 3, där alla fordon antas vara hybridfordon som drivs av halmbaserad bioetanol och el. I detta scenario antas det att fordonen drivs med bioetanol vintertid och med el under sommartid då elproduktionen från solceller på regionens byggnader är hög. Trots det minskade behovet av bioetanol i scenario 4 jämfört med scenario 3 så räcker inte den regionalt tillgängliga halmen för att täcka behovet av bioetanol. Om den tillgängliga ytan som idag ligger i träda antas producera halm kan 30% av etanolbehovet i detta scenario täckas. Den totala verkningsgraden för det integrerade systemet är högre för detta scenario jämfört med S3.

Driftprofilen i S3 visar att alla kraftvärmeverk med integrerad bioetanolproduktion är i drift under hela året på grund av det höga behovet av bioetanol. I scenario 4, där hybridfordonen drivs med el under sommaren, sker ingen bioetanolproduktion under sommaren och istället har man en högre produktion i kraftvärmeverk utan bioetanolproduktion och i värmeverk jämfört med S3.

Polygenerering med integrerade bioetanolproduktion i kraftvärmeverk leder till ökad elproduktion från kraftvärmeverken vilket gör att elimporten kan minskas. I S4 med hybridfordon med eldrift på sommaren ökar elbehovet i regionen. Både kraftvärmeverk och solceller på regionens byggnader kan dock bidra till elproduktion även om inte hela behovet kan tillgodoses.

Alla scenarier har också jämförts vad gäller elimport, bränsleanvändning, produktionskostnader i systemet och CO_2 utsläpp. Vad gäller elimport visar S1, med ökad användning av värmepumpar, högre total elimport jämfört med S2, med ökad användning av elfordon. Toppvärdet för elimporten under en dag är dock ungefär den samma för båda scenarierna. Scenarierna S3 och S4, med integrerad bioetanolproduktion, har betydligt lägre elimport än S1 och S2.

De fossila CO_2 utsläppen från systemet i regionen är lägst för S1, med 30% ökad användning av värmepumpar. På grund av den höga elimporten i detta scenario är dock marginalutsläppen de största för detta scenario. Produktionskostnaden är också låg för detta scenario då drifttiden för kraftvärmeverken minskar. Också för S3, med polygenerering, är de fossila CO_2 utsläppen låga men systemkostnaderna är höga på grund av behovet av import av halm. Vad gäller bränsleanvändningen är den störst för S3 och minst för S1. Skillnaden i produktionskostnaden är dock inte så stor mellan S1 och S4.

Slutsatserna av denna studie kan sammanfattas i följande punkter:

- **Ökad energitillförsel från förnybara energikällor**

  Med ökad elproduktion från installation av solceller på taken till regionens byggnader kan drifttiden för kraftvärmeverk komma att minska och behovet av att köra kraftvärmeverken under sommaren kan försvinna. Elimporten kan också minska under sommaren då solelsproduktionen är hög. Det kan ändå kvarstå problem med kapacitetsbrist för import under vinterdagar.

- **Optimering av möjliga extrema fall för energisystemet**

  Ökad användning av värmepumpar som den primära uppvärmingskällan i enfamiljshus ökar tiden som kraftvärmeverken inte är i drift. En ökning av användning värmepumpar leder till ett ökat elbehov i regionen och då drifttiden för kraftvärmeverken minskar innebär det en ytterligare ökning av elimporten till regionen.

  En ökad användning av elfordon i transportsystemet har inte någon stor påverkan på driften av kraftvärmeverken i de två studerade regionerna.

Elimporten kommer istället att öka. En ökad elimport innebär också ökade utsläpp av CO_2. Fallet med 30% ökad användning av värmepumpar och 100% av eldrivna fordon ger ökade CO_2 utsläpp på ca 40% jämfört med basscenariot.

- **Polygenerering och transportsystem**

  Integration av bioetanolproduktion med kraftvärmeverk kan öka totala värme- och eltillförseln i systemet och elimporten kan minskas, i fallet Västmanland med ca 36% jämfört med basscenariot. Användningen av bränsle till kraftvärmeverken kommer dock att minska då biprodukter och överskottsvärme från den integrerade bioetanolproduktionen utnyttjas av kraftvärmeverken. Ett scenario där hybridfordon som kan använda både etanol och el som bränsle är optimalt både med avseende på energiverkningsgrad, CO_2 utsläpp och total produktionskostnad jämfört med ett scenario med enbart bioetanolfordon i systemet.

Vad gäller påverkan på produktionsplaneringen för kraftvärmeverken så visar studien att scenarierna med ökad användning av värmepumpar och polygenerering med integrering av bioetanolproduktion har en påverkan. Den utvecklade optimeringsmodellen kan användas även för andra energisystem för ökad kunskap om påverkan på produktionsplanering och påverkan av integrerade förnybara energikällor. En intressant fortsatt studie kan vara att undersöka möjligheten för en mer energieffektiv integrerad transportbränsleproduktion med ökad produktion av transportbränsle. Andra typer av bränslen och omvandlingsprocesser, än produktion av bioetanol, kan då vara av intresse. Det kan också vara intressant att undersöka system med mer integrering av vindkraft.

Summary

Due to driving force of increased application of renewable resources and optimal use of biomass resources, the optimization of a more complex system is needed including increased interaction with renewable energy sources such as solar, wind, and hydropower and the limitation in use of biomass. Development of an energy system with more complex situations depends on several key parameters such as the availability of resources, energy demand and consumption behaviour, and product price.

In this project, an optimization model is developed to investigate the effects of the key parameters such as availability of resources, energy demand and supply on production planning of the energy system, considering the whole chain from the inlet fuels to conversion processes and energy products. The objective is to find optimal solutions for cost-effective production and low CO_2 emissions and provide knowledge for operation strategies for the Combined Heat and Power (CHP) plants in the system.

Energy systems in the Counties of Västmanland and Södermanland are used as cases for the study. The systems consist of regional CHP plants integrated with transportation fuel production in a polygeneration design and interacted with local renewable resources including hydropower and solar power. A base case and four optimization scenarios are developed to investigate the system.

The district heat demand in the base scenario is provided by the CHP and heating plants. The power supply from CHP plants together with electric power from the local renewable resources provide the regional electricity demand. A grid-connected rooftop Photovoltaic (PV) system is also defined in the base scenario. The system in the first scenario is similar to the reference system; however, the heat pump is used to replace district heating in the district heat-based buildings by increased utilization shares of 10%, 20%, and 30%. In the second scenario, the energy system operation is evaluated considering the increased penetration of EVs by 10%, 50%, and 100% in the transportation system. In the third and fourth scenarios, a polygeneration system is defined by adding bioethanol production units, which is integrated with the existing CHP plants. Scenario three evaluates the system where all vehicles are fuelled with bioethanol, while hybrid vehicles are considered in scenario four.

The results from different studied cases reveal that the developed optimization model can be used to identify the optimal operation of the energy system for a certain case. Increased applications of heat pumps could affect the system concerning the fuel use and the power import. By using heat pumps, as a replacement for district heat, the demand for district heat will be reduced; thus, the operation time of CHP plants decreases up to around 40%, compared to the reference scenario. Application of heat pumps will increase the power demand, which will increase the power import to the system.

Increased penetration of electrical vehicles influences the plants operation and the power import. In spite of slightly increased power supply from the system, the

electric power import is increased. Especially in the extreme case with 100% penetration of EVs in the system, which leads to an increase in power import of 30% compared with the base case.

The results from scenario three and four demonstrate that the polygeneration design of the system will contribute to increased heat and power production from CHP plants. With application of hybrid vehicles in the regional transportation system, the bioethanol produced from cereal straw can be used as the transportation fuel during winter; while, power generation from CHP plants together with solar power and hydropower will provide the energy needs for the vehicles in summer.

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1 Introduction

Production planning and operation strategies of an energy company is connected to resources availability and use, forecasting of trends in demand, and the production development. Planning the production of an energy system involves the key decisions on the system operation and resource utilization to determine the supply goals to meet the varying demands [1]. Integration of available energy sources with increased use of renewables and different energy conversion technologies in a unique energy system would add importance to production planning models [1,2].

The energy supply from renewable resources is not constant by time and depends on several parameters. For example, power production from solar collectors varies by the weather conditions and the sun position. The same happens for wind power production. Hence, the major challenge in application of renewable resources is to make balance between energy supply and demand. In order to reduce the gap between demand and supply, energy supply from renewables can be integrated with conventional energy systems, which use biomass-origin input fuels to produce end-use energy products.

According to the Swedish statistics (SCB) [3], around 150 TWh power was generated in Sweden in 2015 and hydropower plants accounted for around 47% of the production. Nuclear power is the second major source in power production in Sweden accounting for 34% of the total power production in 2015 [3,4]. Despite the recently increase in electricity generation from wind farms in Sweden, its share in total power generation is still low, around 10% of the production in 2015. Only 8.5% of total nationally produced power is generated in conventional Combined Heat and Power (CHP) plants, of which around 6.3% of the production is based on renewable-based fuels, mainly wood, and 2.2% on other non-renewable fuels [4].

Total heat production from biomass resources has also been increased in Sweden. Around 58% of the total heat demand are generally satisfied by District Heating (DH) networks, producing heat through using biomass-based energy resources such as wood and municipal wastes in CHP plants [3,5]. A large part of the rest is met by electricity-based heating systems including heat pumps and electrical heaters [6]. The production planning of the CHP plants in Sweden depends on the amount of heat supply as the primary product at the plant; therefore, changes in energy use behaviors and future trends in heat demand would sharply affect the operation planning of the system [7].

The transportation sector in Sweden consists of dominantly passenger cars (64% of total vehicle in use [3]), heavy vehicles and trucks, public transport vehicles, trailers, and cross-country scooters. Most of vehicles in use in Sweden are fuelled with petrol and fossil-based fuels. According to the statistics from SCB, the number of petrol-fuelled cars in the domestic transport sector has been reduced by more than 13% [8] over a period of five years from 2011 to 2016. At the same time, the proportion of Electrical Vehicles (EVs) and hybrid cars and vehicles fuelled with biofuels such as biodiesel and bioethanol have increased [8]. The share of the passenger cars fuelled with diesel was a record high in 2012, accounted for 65% of the new cars sold. The share slightly decreased to 58% in 2016. Petrol fueled cars accounted for 36% and EVs, hybrid vehicles and ethanol cars accounted for the remaining 6% in 2016 [4]. The increase in use of bioethanol is mainly due to mixing petrol with bioethanol.

Biofuels can be generated from different types of biomass through different conversion technologies. The energy yield in a stand-alone biofuel production plant is very low. For example, the bioethanol energy yield of the fermentation process is up to 35%, depending on the type of the used feedstock material [9,10], and the residual energy from biomass will appear as waste heat. Another type of biofuel is Hydrotreated Vegetable Oil (HVO) biodiesel that has recently become a popular fuel in the transportation sector. Depending on the type of the used feedstock source, the conversion efficiency of the feedstock to HVO biodiesel would differ [11]. For instance, the yield of the HVO biodiesel produced from tall oil, which is a commonly used feedstock in Sweden, is 52%; while, the efficiency will be lower (around 39%) for HVO biodiesel from logging residues [12].

Due to competition between food and energy supply and restrictions in use of biomass resources, it is important to use available energy resources in an optimal way, especially in the ethanol production processes, where the production efficiency is low. One possible solution is to apply polygeneration design in the energy systems [9,13] to produce multiple products.

A polygeneration approach would increase the overall efficiency of the system, therefore, with certain amount of input fuels more energy products could be generated compared to the conventional stand-alone systems. Therefore, to optimize the energy systems with polygeneration design and increased interaction with renewables, a wide-ranging model needs to be developed with respect to the production strategy of the system as well as considering the whole chain from available resources to the energy outputs from the system.

Serval studies and investigations have been done on production planning of different energy systems; however, review of the current investigations show that most of the models do not include the optimal utilization of the energy resources as the objective. In addition, energy optimization is mostly done at component level in an energy system and there is a lack of studies on the optimization and production planning of the energy plants at large scale including the key parameters in the supply chain. Therefore, the current research project evaluates the optimal way of using available energy resources as well as planning the production from a regional energy system with the aim to increase the overall production efficiency of the system.

1.1 OBJECTIVE

The production of power from CHP plants depends on the heat demand. It means that during the cold days of the year with high heat production, the electricity production will increase following the power-heat ratio at the plant. The reverse situation occurs during summer when the heat demands decrease. The lack of power generation could be satisfied by several renewable sources such as solar energy or hydropower. Therefore, the interaction of CHP plants with other renewable energy utilization, such as wind, solar and hydropower will be more important.

Considering the driving force of increased use of renewable energy sources for reduced environmental impacts, there is a need for development of more complex energy systems with utilization of different biomass and waste feedstock. Application of biomass-based fuels in vehicles together with increased use of EVs and hybrid cars could be one of the effective solutions to meet the Swedish government's target for the energy system in 2030, where the transportation system is to be independent of fossil fuels [14]. This means that the petrol and diesel used as transportation fuels need to be substituted with biomass origin biofuels such as ethanol, HVO biodiesel, and methanol or electricity. Therefore, polygeneration of heat and power in conventional CHP plants with integrated production of transportation fuel, or other high value products can be suggested as a cost-effective and optimal solution.

Polygeneration, increased interrelation with renewables, and changes in weather, fuel and electricity prices, future trends in energy demands and complex interrelations of different parameters add new dimensions to optimization of the system. Simulation tools can give a better understanding of the interrelations. Considering the new approach in energy systems with increased use of available renewable resources, the main objectives of this work are as follows:

1. Development of an optimization model for increased knowledge of production planning and operation strategies for CHP plants, including the whole chain from feedstock availability to customer energy use, as well as integration with transportation fuels production and interaction with regional wind, solar, and hydropower.
2. Identify possibilities to improve energy supply through polygeneration at regional scale.
3. Influence of increased application of available renewable energy sources in a regional energy system and transportation sector.
4. Provide recommendations for system's production plan, which can be applied to energy companies.

1.2 PURPOSE

Considering the increased utilization of biomass-based fuels in energy supply and due to low energy density of this type of feedstock, it is important to evaluate the energy system at local and regional level to be able to estimate potential energy supply under the regional conditions.

In this project, optimization models have been developed to investigate the influence of different parameters on production planning of CHP plants considering the whole chain from availability of feedstock to the customer energy use towards more cost-effective production and lower greenhouse gas emissions. Integration of the studied CHP with transportation fuel production and interaction with regional wind, solar and hydropower are evaluated. The use of biomass and waste as fuel make the production planning task, including feedstock availability and supply, dependent on the regional situation. Optimization cases are developed from regional energy system models for the County of Västmanland and the County of Södermanland in the central part of Sweden.

Regional models have previously mostly been used for planning and finding locations for new installations but in this project we will focus on support for production planning connected to the heat and power plant operation in a system with interaction with renewables and the transportation sector. The influence of operating strategy on feedstock utilization and greenhouse gas emissions is investigated. The aim has been to be able to formulate models for the regional energy systems in Västmanland and Södermanland and provide recommendations on possible operation strategies in a more complex energy system based on the simulation and optimization of extreme scenarios.

The regional energy system including the transportation sector is modeled and investigated for the following optimization cases:

- Increased solar power production through installation of grid-connected solar collectors on rooftop of the buildings in the studied region.
- More application of heat pumps in the system to provide part of the regional heat demand.
- Integration of existing CHP plants with bioethanol production from available cereal-straw in the region.
- Increased utilization of EVs, biofuel vehicles and hybrid vehicles in the regional system.

2 Background and Related works

Optimization of CHP plants has been studied for a long time. Many optimization models have been continuously developed considering different market conditions and parameters, for example the European liberalized electric power market [15]. A number of studies have also been done on integration of different types of biofuel production with CHP in a polygeneration design. The focus in most of the investigations is on cost evaluation of biofuel production and the influences that the system might have on DH networks [16,17]. According to Rong and Lahdelma [18] further development of optimization tools for real-time management of polygeneration systems are necessary due to the more complex situation including interaction with renewable energy sources like hydropower and solar power. They also mentioned that the special conditions for biomass compared to other renewable resources concerning its availability and the energy density would create other types of limitations for energy supply in the system. A literature review of studies on polygeneration and production planning, and on interaction of renewables with conventional energy plants is presented in this section.

2.1 OPTIMIZATION OF POLYGENERATION SYSTEMS

Polygeneration refers to a system where multiple energy products such as power, heat and biofuels can be produced. One such system can be integrated bioethanol production from biomass with CHP plants. In general, polygeneration design would increase the energy supply in the system or the system efficiency. The energy efficiency in a stand-alone biofuel plant is relatively low. For instance, the production efficiency of the fermentation process can be up to around 35% [9], and the residual energy from conversion processes will appear as waste heat. However, through polygeneration, by-products from the biofuel production can be utilized in the CHP plant for further heat and electricity supply. The waste heat from the fermentation and conversion processes can also be used in the DH network.

This topic has been the focus of several studies in recent years. For instance, Salman et al. [19] studied the methanol production through integrated gasification with a local CHP plant in a city in Sweden. Different alternatives to achieve a fossil fuel free energy system in Mälardalen regions in Sweden have been addressed and investigated by Dahlquist et al. [20,21]. The influence of a regional polygeneration system on lingo-cellulosic ethanol yield and the operation of an existing CHP plant were evaluated by Starfelt et al. [22,23]. The study evaluated the impacts of adding an integrated ethanol production to an existing CHP plant. In a similar works, which are done by [9,24] the effect of integrated ethanol production into DH networks is investigated.

Optimization models for production planning and energy system analysis are often based on Mixed Integer Linear Programming (MILP). An example of such model that has been applied for different regional energy systems is the BeWhere model. The model has been used to find the optimal locations for building new energy conversion plants and optimal combination of different conversion technologies both on regional and country level in different parts of the world [25–28].

A dynamic model based on MILP method has been developed for regional CHP plants integrated with biofuel production in the County of Västmanland in Sweden, with the aim to optimize a waste to energy system concerning GHG mitigation and minimizing the system cost [29]. The focus of the study was to address the possibility of developing a regional fossil fuel free energy system using biomass-based energy resources. Daianova et al. [16,30], in another study, apply a MILP dynamic model to evaluate the integrated transportation biofuel production in the Sala-Heby region in Sweden using locally available crops with a focus on CO_2 emission mitigation. They also conducted a techno-economic analysis in another investigation to evaluate the influence of key parameters including feedstock cost and petrol price on the performance of a regional CHP plant integrated with straw-based biofuel plants. The results from comparing the stand-alone biofuel production with polygeneration system showed that the integration design of the system could lead to a decrease in production cost by around 31% [16].

An integrated energy system was also optimized by [31] using MILP method with the aim to investigate the increased cogeneration of clean energy. This was a case study in one city in Sweden to find the impacts of integration of a paper-manufacturing mill with biofuel-based CHP plants on the energy efficiency and system cost in DH network. The main conclusion of the above-mentioned studies was that the integration of different energy conversion technologies in one energy system could have a large influence on the overall efficiency of the system. It was shown that polygeneration design would lead to increased energy supply from the system with use of certain amount of fuel, compared to the stand-alone energy plants. This concept is used as the basis of the current research project.

Gustafsson et al. [6] have conducted a case study in a city in the middle of Sweden to find possible alternatives or solutions to reduce the peak power demand. Different future scenarios have been developed to evaluate the potentials considering the shares in the heat market regarding DH production and electric heating sources. Increase of other electricity production technologies has not been considered in this study. According to the analysis, type of the source used for heating purposes has higher influence on reducing the peak demand than the reduction in heat demand. Moreover, the peak power demand can be covered using CHP plants in the municipality, where the DH has the larger part of the heat market. No model is developed in this study and the analysis is based on statistics and scenarios developed by European nations.

Lund et al. [32] showed the potential for large-scale heat pumps that can be used in DH network in Denmark and the feasibility of such strategy from an economic perspective. The sensitivity analysis in this work showed the dependency of the system performance on the electricity and input-fuel price. The study mainly addressed the DH production with no investigation on either the electricity demand or the interaction of heat pump utilization as the main heating source in the buildings.

2.2 INCREASED INTERACTION OF RENEWABLE RESOURCES

By including wind, solar and hydropower the polygeneration system will include also distributed power generation. Capuder and Mancarella [33] provided a MILP modelling and optimization framework to evaluate the production planning of distributed multi-generation systems for DH systems including CHP plants, heat water boilers, and electric heat pumps. However, the electricity generation from wind, solar and hydropower is not included in their model. Integration of CHP plants with renewable resources and technologies for clean energy supply will influence the system operations and the energy efficiencies. This also influences and/or depends on the energy prices, energy demand, weather condition and CO_2 emissions.

According to Rong and Lahdelma [18] not much research has been done on optimization of systems including both central and distributed systems but they point out that the approach presented in their previous work on multi-site combined heat and power production should be possible to use.

As pointed out by Shaoa et al. [34], increased use of renewable resources in conventional energy plants will lead to more flexible operations in the energy system. Several studies systems can be found for some European countries investigating the integration of CHP-based DH with renewables and optimization of polygeneration [16,29,31,35,36].

Wang et al. [36] have conducted a study on the impacts of thermal solar energy and thermal storage on the production planning of the regional CHP plants in Finland. Their analysis showed that the system would lead to a more fluctuating heat load and higher share of renewable resources in the case study system.

There are few studies with the focus on evaluating the potential electricity generation from local renewable resources in interaction with conventional thermal plants. For instance, three different scenarios were developed in a study for western Finland to investigate the optimal combined energy supply to satisfy the regional electricity demands [37]. The study results imply that distributed energy system in the region together with local wind power production and hydropower is more optimal than the system with use of biomass and PV cells application.

In a case study for Denmark, Lund et al. [35] showed the possibility to increase the flexibility of the energy system through integrating CHP plants with heat pumps and wind power. They concluded that the share of wind power production could possibly increase in such flexible system. The study focuses on creating a balance in the system, between electricity demand and supply, and compensating the lack of production from wind power plants by generation form CHP plants.

According to SCB, the number of petrol-fuelled cars in transportation system in Sweden has been reduced by more than 13% from 2011 until 2016 [4]. While, the share of EVs and hybrid cars in the road traffic has increased. The trend for use of biofuel cars is also increasing; however, the transportation system still relies on fossil fuels as the main energy source in domestic transportation sector. Therefore, further approaches concerning CO_2 emissions mitigation need to be implemented in the energy system.

Several studies have been carried out to find suitable renewable-based alternatives replace conventional fossil transport fuels.

Turner et al. [38] have investigated the possibility to use a ternary blend of gasoline, bioethanol, and biomass-origin methanol (GEM) as fuel in flex-fuel vehicles. The results showed that with the proposed fuel, utilization of ethanol in road traffic will increase and the fuel can displace petrol from the transportation system, which consequently reduce emissions. Aldenius et al. [39] have studied the motivations and challenges that might occur to apply renewable fuels such as biogas or bioethanol in public transportation vehicles like busses in European countries. GHG reduction for higher air quality was one of the most important motivations proposed in this study, however, biomass availability and increase in biofuel production were considered as big challenges.

The availability of feedstock is one of the key constraints in regional biofuel production. Since domestic ethanol production is lower than the demand in Sweden, a great share of the demand are met by biofuel imports [30]. The weather condition is one of the restrictions for domestic production. Therefore, cultivation of different energy crops in the suitable location considering the Swedish climate and agriculture could be a possible solution to increase the local feedstock used for biofuel production.

The input fuels used for biofuel supply are divided into three categories: I) sugarcane and food residues such as cooking oil, wheat, barley and corn, II) wood, agricultural residues including seed crops and cereal straw, and municipal waste, and III) algae.

Studies on analyzing the potentials for feedstock supply for biofuel production are generally done at small scales like a city or large scale like a country [30,40,41]. In a study, Grahn et al. [42] showed the increased potential biofuel production in Sweden by 2030, through expansion of different type of biofuels production using new supply facilities. The approach can lead to the maximum biofuel share of 79% of the total energy use in Swedish transportation system by 2030. Any other changes such as inclusion of more energy efficient vehicles like EVs are not included in the study.

Ekman et al. have done a similar study on feasibility of biofuel production from agricultural residues in Sweden and investigated the technical aspects of biomass conversion to biofuels [43]. According to their research findings, straw, as one the most available biomass around the world, is suitable to be used for production of biofuels. They found that to increase the efficiency of conversion processes of straw to biofuel and the economic profit of the system, the excess heat from bio-refinery system can be used in DH networks.

3 Method

To achieve the objectives of the project, the following methods have been applied:

- Data collection: data needed for modelling are collected for the region. Available databases and general data sources have been used, and data has been further treated to prepare regional statistics for energy systems in Västmanland and Södermanland (case study regions).
- System configuration: the parts of the system, such as type of fuels, conversion processes, energy products, etc. that should be included in the optimization model, are identified.
- Modelling & optimization: Modelling, simulation, and optimization of the studied CHP plants integrated with regional renewable resources (wind, solar, and hydropower) and bioethanol production were done by developing a MILP model formulated in General Algebraic Modelling System (GAMS). Optimization cases are developed for the energy systems in Västmanland and Södermanland.

3.1 CASE STUDY

A MILP optimization model is developed for a regional energy system including the chain from utilization of biomass and waste as the input feedstock to the final energy use. The energy systems in Västmanland and Södermanland, two Counties in the middle parts of Sweden, are used as case studies for the model.

Västmanland is a County in central Sweden consisting of ten municipalities with a total population of around 271 000 in 2015 and a land area of 5 118 km^2 [44,45]. The regional energy system consists of 34 energy plants including CHP and heat water boilers , 30 hydropower stations with total peak power of around 51 MW, and one solar park with 90 solar collectors with total capacity of 1 MW [46]. There are five CHP plants in the system producing roughly 250 GWh electricity and 1 579 GWh heat [47]. Biomass-based fuels are dominantly used in the plants together with a small share of fossil fuel, like oil and peat mainly used in heat water boilers.

The County of Södermanland, with nine municipalities, has a population of 291 340 and a total land areas of 6 075 km^2 [44]. There are around 22 energy plants in the regional energy system of which four are CHP plants and the rest are heating plants. Wooden biomass is mainly used as fuel in the energy conversion processes in Södermanland; however, fossil fuel oil is also used in some of the heating plants. The renewable energy sources in the region consist of 18 hydropower plants with a total power of around 9.5 MW [48], two solar cell parks, one with low capacity of 170 kW and the other one, which is bigger, produces around 1 GWh power per year [49]. There are also nine wind power farms with total installed capacity of 7 MW in Södermanland [50,51].

Figure 3-1 shows a map of the studied Counties in this study with the location of the energy plants in the regions.

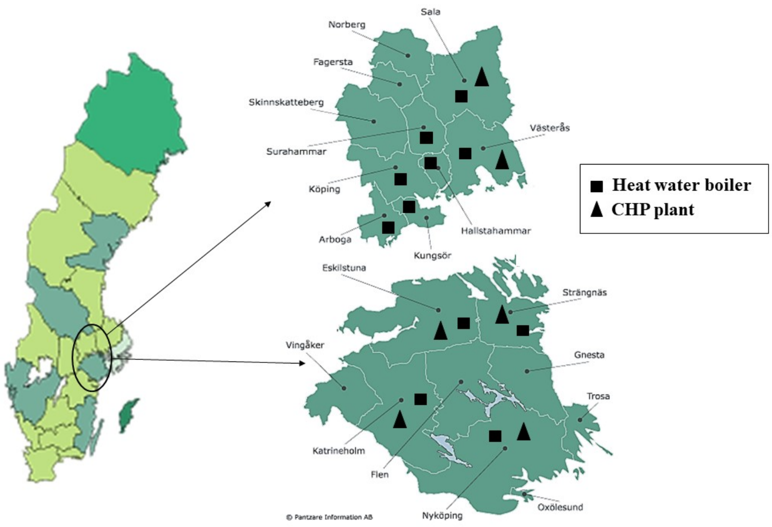

Figure 3-1 Map over the studied regions [72].

3.2 DATA COLLECTION

In this study, the operational strategy of the energy system on daily basis is investigated using the results of simulations with a model developed for the regional energy systems. Several parameters could influence the production planning of an energy system. Concerning the input fuels, availability and fuel price are some of the key factors that would affect the amount of fuel used in the energy system. From the energy supply perspective, the energy demand in the form of heat, power, and transportation fuels is the essential parameters, which could have a significant influence on the plants operation. The conversion technologies and system efficiency are other important factors affecting the energy supply and add new dimensions to the optimization model. Therefore, recognizing the main parameters and modelling data play an important role in optimization problems. The needed data for the optimization model in this study and how they are found is divided into three parts including the data for energy plants in the region, for local renewable energy resources, and for the regional transportation system. All used parameters in the study and the source where the data has been collected can be found in Appendix A.

3.2.1 Energy system

The feedstock used in the regional system includes oil (both fossil and bio based), coal, peat, wood chips, municipal waste, wood pellet, and biogas. The model considers the possibility for exporting and importing fuels and energy products.

The input data for the energy system includes the amount of available and imported fuels and the production cost or importing price of the input fuels, conversion ratio of feedstock to energy products and energy conversion cost, the production capacity of each plant, and the price of energy products. The energy supply from plants to cover the energy demands in the region is restricted by the limits of available biomass, the maximum production in each plant and the regional demand for heat, power, and transportation fuels. More details on input data can be found in Appendix A.

The CO_2 emissions from conversion of input fuels to the final energy products is considered in the optimization model. Emissions are dominantly from the energy processes in the system, however, the marginal emissions from energy products imports are also considered. Feedstock preparation and conversion processes at plants would emit some CO_2.

CO_2 emissions from plants are divided into biomass-based and fossil-origin CO_2. In this study, oil, coal, and peat are assumed to emit fossil-based CO_2. A proportion of municipal waste also contains fossil fuels. Therefore, municipal waste combustion could add some fossil-origin CO_2 to the environment.

According to the study by Song et al. [29], CO_2 emissions from transportation of fuels accounts for less than 1% of the total emissions of using the fuel. Therefore, it is not considered in the model. However, the marginal fossil-based CO_2 emissions from importing the electricity are included in the calculations [52].

3.2.2 Regional renewable resources

Amongst local renewables, hydropower is the main source, which contributes to a great proportion of the total regional power needs. There are several hydropower plants, both small and big, in both regions [48].

The capacity of solar power and wind farms in the studied regions is low. There is only one solar park with a power of 1 MW in Västmanland and no wind farm in big scale in this region. The existing solar power plants in Södermanland are also small.

The potential electric power supply from solar power is considered in this study. A maximum power production from solar collectors, which are installed on the rooftop of the buildings in the region, is estimated and included in the model. To do such estimation, parameters such as number of buildings and available areas for panel installation, solar radiation and weather conditions, and the panel efficiency and performance ratio need to be specified.

3.2.3 Transportation system

The main parameters needed for evaluating the regional transportation systems consists of the total number of vehicles in use in the transportation systems, type of the vehicles and transport fuels, the distance that is covered by each vehicle and the energy content of the fuel.

Since the resolution of the model is per day, the average mileage driven by each type of vehicles per day needs to be estimated.

In this project, biofuel production integrated with CHP plants in a polygeneration design is investigated. The straw from cereals comprising wheat, oats, and barley is used as the fuel input to the biofuel plants. The available straw in the region depends on the available area for cereal production and the amount of cereals cultivated in the region. Therefore, the potential straw production in the base studied year is estimated using the data on available agricultural land and the productivity of the crops under the agricultural conditions in the region, as well as the ratio of the residues to the produced cereal. In order to prevent the soil erosion and to maintain its productivity, a share of the residues or straw has to be ploughed into the land.

3.3 DATA TREATMENT AND PREPARATION

Most of the data collected from available databases were on yearly or monthly basis. Since the resolution of the model was set per day, some of the parameters, such as district heat and power demand needed to be recalculated to find the variations per day.

To find the demand variations by day, the real-time data for district heat demand in one municipality in Västmanland is used. Given the total yearly district heat demand for each municipality in the region, daily variations of heat demand in one municipality (the capital city of Västmanland), and the weather conditions concerning the outdoor temperature in different days in the studied region, further estimation is done to find the daily district heat demand in the region. The amount of district heat delivered to the DH network per day in the capital city of the County is provided by the energy companies. Assuming similar weather condition in other cities in the region, the same variations of the demand over the year are assumed and the demand per day is calculated based on this.

As the monthly variation of the district heat use in Södermanland was almost the same as the demand in the County of Västmanland, the same method is applied to find the demand data per day in Södermanland.

The data on used fuels in the base year was not available for some of the CHP plants and heat water boilers in the County of Södermanland. Hence, the reported data in other years after 2015 by corresponding energy companies are compared and similar values or average data are used for parameters in the base year. Depending on the type of fuels used in each plant, the total available woody biomass at some of the heating plants in Södermanland is estimated through the backward calculation using the maximum produced energy at the plant and the production efficiency, with respect to the energy balance.

Due to lack of information, the input values of some parameters for modelling are estimated using assumptions in other studies and similar literature. For instance, the similar study by [13] is used to estimate the capacity of bioethanol plants. The importing price of the cereal straw used in the investigation done by Daianova et al. [16] are applied as the input data to model the polygeneration system.

According to the statistics from SCB, most of the multi-family houses have a floor area in the range from 60 to 90 m^2, while the range are bigger for single-family houses and public buildings, from 60 m^2 to 150 and 100 m^2, respectively. There is an exception in the floor area for single-family houses in Södermanland and the majority of houses of this type have a floor area from 60 up to 120 m^2. To estimate the available area for solar panel installation, only buildings with floor area greater than 60 m^2 were considered.

To find the available rooftop area for multi-family building, the given data from SCB on number of dwellings in multi-family buildings is divided into the number of buildings of this type, which is roughly estimated based on the QGIS data provided by the Municipality authorities [53]. Therefore, with consideration of an average floor area for different buildings in each County and 6.5 dwellings per multi-family building, the total rooftop area could be estimated for panel set up in the region using the equation below:

$$A_{total} = \sum_{t=1}^{T} N_t \times A_{r,t} \quad (1)$$

Where N_t is the number of buildings of type t, and $A_{r,t}$ is the rooftop area that is estimated for buildings of different type in each studied region based on the building's floor area.

Due to the limited data on electricity import, which is one of the important parameters in evaluating the optimization model, the maximum power import during 2015 is used as the maximum daily power import. The difference between the amount of power generated, according to the model, and the demand provides information on the amount of imported power that is compared with the assumed maximum import in the region.

The demand for transport fuels should be estimated in order to develop the optimization model for the integrated system with polygeneration of bioethanol. Since there is also lack of data on fuel use at regional scale, the suggested equation by Daianova et al. [30] (eq. 1) is used to estimate the fuel demand in the regional transportation system. Parameters such as the number of vehicles by type of the fuel use (N), average distance in kilometer covered by each vehicle (S), average fuel consumption (litter) per driven kilometre (Q), and the energy content of the type of fuel in kWh per litter (E) are used to calculate the demand:

$$Demand = N \cdot S \cdot Q \cdot E \quad (2)$$

3.4 SYSTEM CONFIGURATION

As it is mentioned in previous sections, a MILP model is developed for the energy system in the region including heat water boilers and CHP plants, which is integrated with transportation fuel production. The system also interacts with regional renewable resources, solar, wind, and hydropower, to investigate the influence of increased application of renewables on flexibility of production from CHP plants. The impacts of other parameters such as fuel price, integration of biofuel production, and trends in energy demand and supply are also considered in the evaluations. Industries in addition to energy companies, can contribute to the energy supply. In the model, waste heat from industries is included by reducing the heat demand by the utilized industrial waste heat. The system configuration diagram is shown in Figure 3-2.

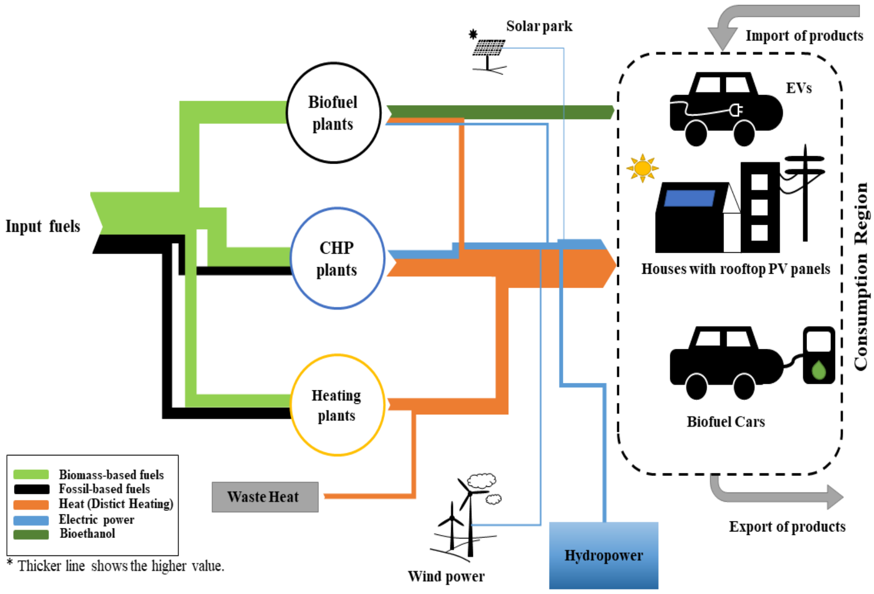

Figure 3-2 Schematic view of the studied system.

3.5 MODELING AND OPTIMIZATION

The energy system is modelled using MILP method. The parameter sets used in the model are F, the number of input fuels, N, the number of products, P, the number of plants and D, the number of days in one year. Therefore, the corresponding data sets are defined as $\widetilde{F} = \{1, \ldots, F\}$, $\widetilde{N} = \{1, \ldots, N\}$, $\widetilde{P} = \{1, \ldots, P\}$, and $\widetilde{D} = \{1, \ldots, D\}$. The variables and parameters used in the model equations are described in Table 2.

Table 1 Variables and parameters used in the developed MILP model.

Variable/Parameters	Unit	Description
$F_{f,p,d}$	ton	Amount of available regional fuel f in plant p in the day d
$F_{f,p,d}^{imp}$	ton	Imported fuel f to the plant p in the day d
$c_{f,d}^{F}$	SEK/ton	Cost of fuel f in the day d
$c_{f,d}^{F,imp}$	SEK/ton	Importing cost of fuel f in the day d
$pc_{f,p,d}$	SEK/ton	Conversion process cost of fuel f in the plant p in the day d
$q_{n,p,d}$	MWh	Product n delivered from production plant p in the day d
$q_{n,d}^{imp}$	MWh	Imported product n in the day d
$q_{n,p,d}^{exp}$	MWh	Product n from the production plant p exported to the external market in the day d
$c_{n,d}^{q}$	SEK/MWh of product	Price of product n (imported or exported) in the day d

Variable/Parameters	Unit	Description
$V_{p,d}$	-	Operation status of the plant p in the day d
H_d^{Waste}	MWh	Recovered industrial waste heat in day d
c^{waste}	SEK/MWh	Cost of waste heat

3.5.1 Mathematical model

The following equations and constraints are defined for the rooftop PV systems, bioethanol production integrated with CHP plants, and heating plants including fuel use, conversion processes, and production cost.

3.5.1.1 CHP and heating plants in polygeneration system

To develop the optimization model for the polygeneration system, an energy balance between input and output energy in the plants is formulated including also possible exports to other regions.

$$\sum_{f=1}^{F} \left(F_{f,p,d} + F_{f,p,d}^{imp}\right) \times Conv._{f,p,n} = q_{n,p,d} + q_{n,p,d}^{exp} \qquad (3)$$

$$p \in \tilde{P}, n \in \tilde{N}, d \in \tilde{D}$$

Where $Conv._{f,p,n,d}$ is the conversion rate of the fuel f in the plant p to product n in the day d. The power to heat ratio in CHP plants, which is called the Alpha (α) value shows the relation between the power generation to the heat that is produced from the plant.

$$\propto = Power\ generation/Heat\ supply \qquad (4)$$

The Alpha value at CHP plants is estimated to be around 0.48 based on the real data from energy companies in the region [47].

The equations suggested by Daianova et al. [16] with some modifications are used to find the conversion rate of fuel to heat and power production at the ethanol plants:

$$Conv._{f,p}^{H,Eth} = \propto_p^H \times \eta_p^{Eth}$$

$$Conv._{f,p}^{El,Eth} = \propto_p^{El} \times \eta_p^{Eth} \qquad (5)$$

In the equation, parameters $\propto_p^H$ and $\propto_p^{El}$ show the ratio of heat and power production to ethanol production, and η_p^{Eth} is the parameter for ethanol production-to-inlet fuel ratio [13,16,22].

The energy supply from each plant is limited by the production capacity of the plant:

$$\sum_{f=1}^{F} \left(F_{f,p,d} + F_{f,p,d}^{imp}\right) \times Conv._{f,p,n} \leq Q_{n,p,d} \times V_{p,d} \qquad (6)$$

In the expression, $V_{p,d}$ is a binary variable that defines the operation status of the plant. When V is equal to one, the plant is in operation, while the plant is shut off, when V is zero. Parameter $Q_{n,p,d}$ is the limit to supply product n in the plant p. In other words, Q shows the plant's capacity.

The study done by [13] are used as the reference to estimate the maximum biofuel production from the integrated biofuel plants concerning the plant capacity and conversion ratio of inlet fuels to energy products:

$$Capacity\ of\ ethanol\ plants = \dot{m}_f^{Eth} \times \eta_p^{Eth} \tag{7}$$

Parameter $\dot{m}_f^{Eth}$ is the maximum inlet energy flow in MW/h to the ethanol plant.

The constraints for the available fuels in the plants used per day and the imported amount of fuels to the plant are shown in equation (8) and (9), based on the maximum amount of available fuels at the plant and imports limits, respectively.

$$\sum_{p=1}^{P} F_{f,p,d} \leq F_{f,p,d}{}^{Available} \tag{8}$$

$$\sum_{p=1}^{P}\sum_{d=1}^{D} F_{f,p,d}^{imp} \leq F_f^{imp-Limit} \tag{9}$$

Since the demand and the level of production might change over time, the limit of energy demands is formulated by an inequality (equation (10)) in the model. The contribution of local industrial waste heat in heat production is also considered in the equation. As can be seen in equation (10), the lack of energy products can be met by importing products.

$$\sum_{p=1}^{P} q_{n,p,d} + q_{n,d}^{imp} + H_d^{Waste} \geq Demand_{n,d} \tag{10}$$

The model includes possible utilization of waste heat from industry, therefore, the purchasing cost for the waste heat is considered in the production cost.

Finally, total production cost for all plants in the integrated system can be expressed by the following equation:

$$\begin{aligned} Cost(f,q,v) = & \sum_{d=1}^{D}\sum_{p=1}^{P}\sum_{f=1}^{F} c_{f,d}^{F} \times F_{f,p,d} + \sum_{d=1}^{D}\sum_{p=1}^{P}\sum_{f=1}^{F} c_{f,d}^{F,imp} \times F_{f,p,d}^{imp} \\ & + \sum_{d=1}^{D}\sum_{p=1}^{P}\sum_{f=1}^{F} pc_{f,p,d} \times \left(F_{f,p,d}^{imp} + F_{f,p,d}\right) \\ & + \sum_{d=1}^{D}\sum_{n=1}^{N} c_{n,d}^{q,imp} \times q_{n,d}^{imp} - \sum_{d=1}^{D}\sum_{n=1}^{N}\sum_{p=1}^{P} c_{n,d}^{q,exp} \times q_{n,p,d}^{exp} \\ & + \sum_{d=1}^{D} H_d^{waste} \times c^{Waste} \end{aligned} \tag{11}$$

Where the fuel prices and imports, process cost in the plants, and products export benefit are considered.

As it is pointed out in previous sections, the overall efficiency of the polygeneration system is one of the effective factor in evaluation of the optimization model. Equation (12) is used to determine the efficiency of the polygeneration system (η_{system}).

$$\eta_{system} = (Bioethanol + District\ Heat + Power)/Total\ imput\ energy\ from\ fuels \quad (12)$$

3.5.1.2 Rooftop PV systems

Equation (13) is applied to estimate the energy supplied from the rooftop solar panels, using the available roof area for collector set up, solar radiation in the region, and panel efficiency and performance.

$$E = A \cdot H \cdot r \cdot PR \quad (13)$$

In the equation, A is the available area in m^2, H is the daily average solar radiation in each city in the region (kWh/m^2) [54]. r stands for panel efficiency, which is assumed to be 16% for a type of panel with maximum power of 300 W at standard conditions and PR is the performance ratio with a value of 0.75 [55]. The energy output (E) can be found in kWh with equation (13).

The cost estimation of the PV systems depends on the size and type of the modules, the components used in the system, and the available subsidies for the system [56]. The rooftop PV systems in this study consist of solar collectors, cables, and boxes. Batteries are not considered in the calculations since the PV systems are assumed to be grid connected.

According to [56], the average installation cost for a rooftop PV system in Sweden is around 13 to 14 SEK per peak power in $Watt_{peak}$, which is the maximum power that can be produced from the panels under the standard conditions regardless of the location where they are installed. Assuming a panel size of 1.6 m^2, a standard panel can produce around 270 W power [46]. The price of a panel with a standard size of 1.6 m^2 and a rated power of 270 W can be in the range from around 1700 SEK to 2000 SEK. Assuming the average installation price, the investment cost can be estimated using the total area of the panels.

The annual operation and maintenance cost of the system is very low. The depreciation cost on a certain tax rate and the salvage value of the components after the system's lifetime are also considered as the benefit of the system in the cost estimation. According to the similar assumption used by [57], the salvage value is 10% of the total installation cost. Depreciation (dr) can be calculated by the following equation:

$$dr = \frac{Installation\ cost - Salvage\ value}{System\ life\ time} \quad (14)$$

The final total cost of the studied PV system, without battery, is estimated using equation (15):

Rooftop solar panel cost = Installation cost + Maintenance cost – (Cost reduction due to depreciation + Salvage value)

$$PV\ Cost = Installation\ cost + \left(\frac{mr}{1+i}\cdot(1-tr)\right) - \frac{dr}{1+i}\cdot tr - \frac{S}{1+i}\cdot tr \qquad (15)$$

Where *tr* is tax rate, which is assumed to be 20% in this study; *i* is the interest rate with the standard value of 1.5% in Sweden for PV system. *mr* is annual operation and maintenance cost considered to be 1% of the total investment cost [56].

3.5.1.3 Objective function

The mathematical model is expressed as the following objective function to minimize the total production cost of the studied system:

$$\begin{aligned} Obj.F = {} & \sum_{d=1}^{D}\sum_{p=1}^{P}\sum_{f=1}^{F} c_{f,d}^{F} \times F_{f,p,d} + \sum_{d=1}^{D}\sum_{p=1}^{P}\sum_{f=1}^{F} c_{f,d}^{F,imp} \times F_{f,p,d}^{imp} \\ & + \sum_{d=1}^{D}\sum_{p=1}^{P}\sum_{f=1}^{F} pc_{f,p,d} \times \left(F_{f,p,d}^{imp} + F_{f,p,d}\right) \\ & + \sum_{d=1}^{D}\sum_{n=1}^{N} c_{n,d}^{q,imp} \times q_{n,d}^{imp} - \sum_{d=1}^{D}\sum_{n=1}^{N}\sum_{p=1}^{P} c_{n,d}^{q,exp} \times q_{n,p,d}^{exp} \\ & + \sum_{d=1}^{D} H_d^{waste} \times c^{Waste} + Installation\ cost\ (PV) \\ & + \left(\frac{mr}{1+i}\cdot(1-tr)\right) - \frac{dr}{1+i}\cdot tr - \frac{S}{1+i}\cdot tr \end{aligned} \qquad (16)$$

Finally, the optimization problem for the energy system is defined with the following equations with the aim to minimize the total cost:

Min [Obj.F]
Subject to:
Equations (1) to (10), (13) and (14)

and,

$$F_{f,p,d}, F_{f,p,d}^{imp}, q_{n,p,d}, q_{n,d}^{imp}, q_{n,p,d}^{exp} \geq 0, f \in \tilde{F}, p \in \tilde{P}, n \in \tilde{N}, d \in \tilde{D}$$
$$V_{p,d}, U_{p,d}, O_{p,d} \in \{0\ , 1\}, p \in \tilde{P}, d \in \tilde{D}$$

3.5.2 Model inputs

There are 34 plants in the County of Västmanland including CHP and heating plants. In the study, it is assumed that each existing CHP plant in the region is integrated with a bioethanol production unit. The regionally cultivated and imported cereal straw are used as the inlet fuel for bioethanol production. Characteristics of each plant in Västmanland and Södermanland can be found in Appendix B. The system in Södermanland consists of CHP and heating plants without integration of transportation fuel production.

The daily district heat demand during the reference year 2015 is varying depending on the weather conditions and is shown in Figure 3-3. Although many industries have been identified as the potential suppliers of waste heat in the studied regions, only a few of them are found in the existing system. Around 6% of the total district heat production in Södermanland in 2015 is provided by industrial waste heat. The share is less in Västmanland and the capacity is restricted to around 35 MW.

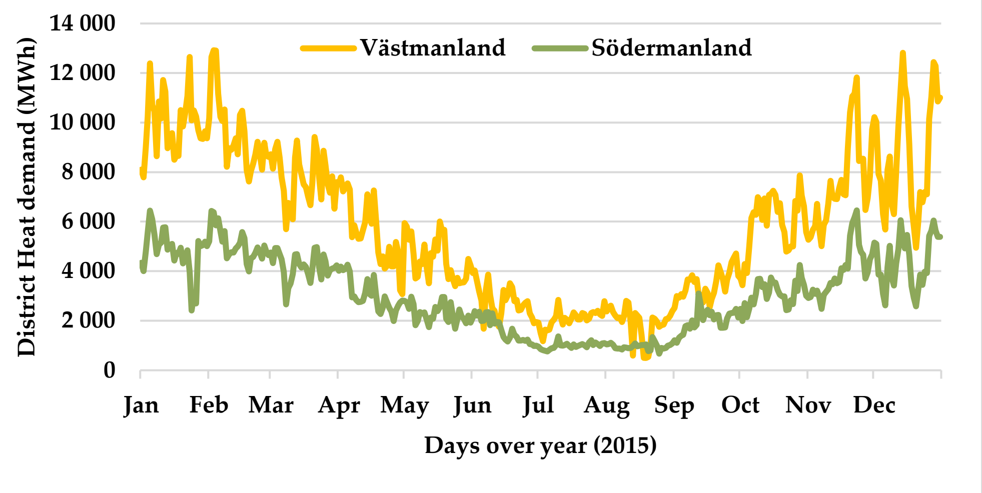

Figure 3-3 The daily district heat demand profile in Västmanland and Södermanland (based on the data from energy companies).

Daily electricity use profiles in the both studied regions by type of the power generation source are shown in Figure 3-4. Since the production from existing solar parks and wind power in the studied regions is low, they are shown together in the graph. The power use is lower in the summer time in both regions compared to the winter time. The increase in demand in winter might be due to increased use of electric-based heating sources. Most of the power demand in 2015, more than 80%, was satisfied by the power import from outside the regions.

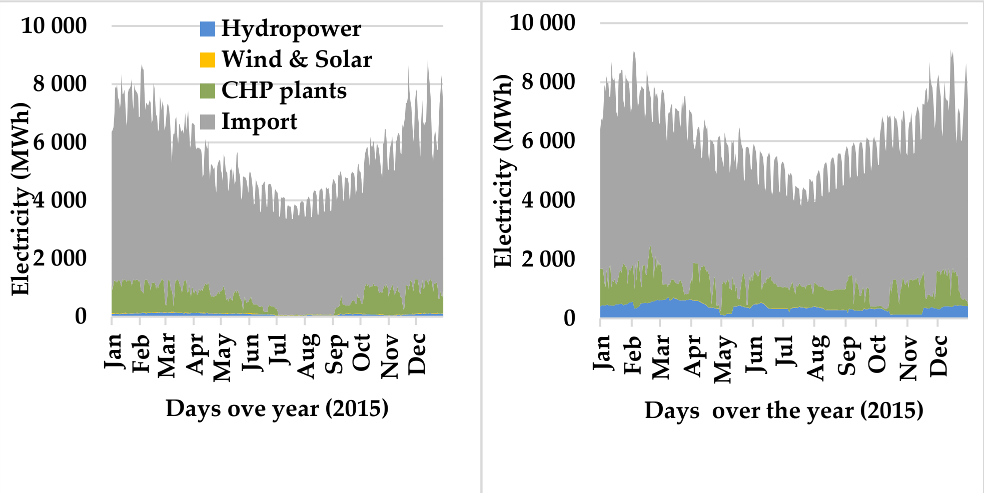

Figure 3-4 Electricity demand profile in Södermanland (left fig.) and Västmanland (right fig.) divided into three local energy sources (hydropower, CHP, and wind & solar plants) and import (based on the data from SVK).

The monthly variations of DH market price, the electricity spot price, and the selling price of ethanol per day are shown in Figure 3-5. The market price for DH is lower in summer due to less demand in this period of the year compared to during winter.

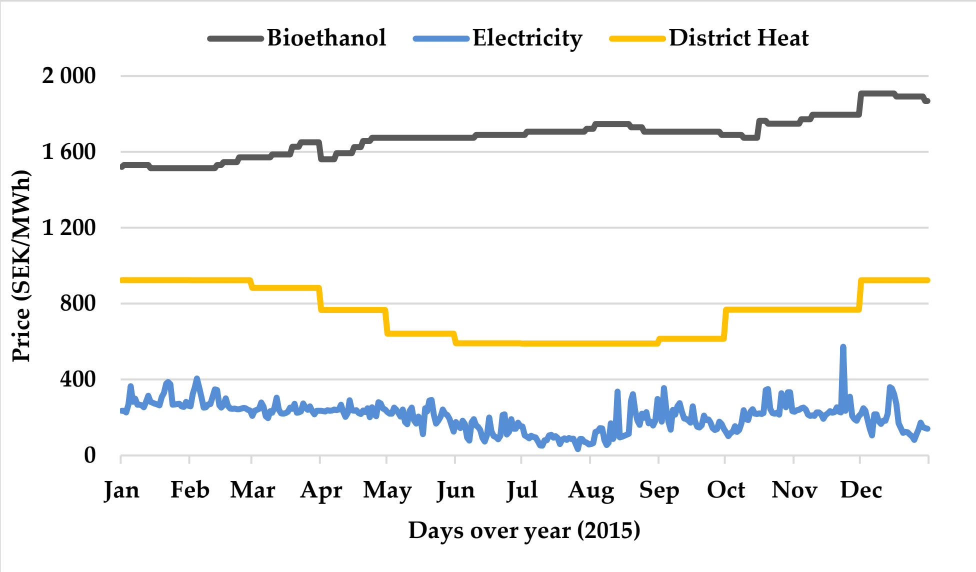

Figure 3-5 Monthly DH market price and electricity spot price over the studied year [50,51,59].

There are 196 850 vehicles of different types including passenger cars, trucks, buses, snowmobiles, etc. in the transportation sector in the County of Västmanland. The passenger cars are the main vehicle type with a share of 66% of total number of driven vehicles [4,8]. Of the 44% of the rest, around 16% are buses, trucks and motorcycles. Most of the passenger cars are fuelled by petrol and diesel, while buses and heavy vehicles run on biogas and diesel. There are 405 buses in Västmanland, and 165 buses are fuelled by biogas [58].

Despite of increasing trend for driving EVs, the share of the vehicles of this type in the region is very small accounting for below 1% of the road traffic in 2015 [8,59]. Utilization of biofuels as transport fuel is also increasing in the Swedish transportation system. There is an increase of 47% in bioethanol-fuelled cars in the road traffic over a period of 5 years from 2010 to 2015 [4].Total number of vehicles in Södermanland are 212 094 including passenger cars, trucks, lorries and trailers, busses, motorcycles and cross-country scooters. Similar to the shares in Västmanland, passenger cars make up the majority of vehicles in use in the regional road traffic, which are mostly fuelled by petrol. The fossil-based fuels are the dominant fuels used for the heavy vehicles in the region. According to regional data, 51 buses of the total number of buses in Södermanland (286 buses) run on biogas and the rest are fuelled by diesel [58]

Utilization of biofuels as the transport fuels has increased during the past years [4]. Most of the increase is due to the increased share of ethanol in the conventionally used petrol, as well as increased use of biogas. In Västmanland, around 34% of the busses and less than 1.5% of the trucks run on biogas [58]. The shares in Södermanland are the same (1.5%) for trucks and around 18% for busses.

The transportation fuel demand is shown in Table 3 (the assumptions and estimation method are described in section 3.3).

Table 2 Fuel use per day by type of the fuel and vehicle in the studied regions [4,8,60–63].

	Passenger cars					Trucks		Buses		Motorcycle
	Petrol	Diesel	Ethanol	Biogas	EVs	Diesel	Biogas	Diesel	Biogas	Petrol
Number of vehicles (Väst.[1])	87 073	35 239	6 919	848	765	13 849	158	270	137	9 264
Number of vehicles (Söder.[2])	94 541	35 906	7 261	1 045	1 236	16 283	252	235	51	11 212
Average distance covered by vehicle, Väst. (km/day)	32	32	32	32	32	46	46	153	153	5
Average distance covered by vehicle, Söder. (km/day)	33	33	33	33	33	46	46	170	170	5
Fuel use per km by type of the fuel (liter/km)	0.08	0.056	0.11	0.045[3]	-	0.36	0.9[3]	0.28	0.52[3]	0.08
Fuel use per km by type of the fuel (kWh/km)	-	-	-	-	0.15	-	-	-	-	-
Energy content of fuel (kWh/liter)	9.04	9.7	6.24	9.8[4]	-	9.7	9.8[4]	9.7	9.8[4]	9.04
Total fuel use by type of fuel, Väst. (MWh/day)	2 015.08	612.54	151.97	11.97	3.67	2 224.59	64.10	112.2	106.82	33.50
Total fuel use by type of fuel, Söder.(MWh/day)	2 256.28	643.64	164.47	15.21	6.12	2 615.57	102.24	108.5	44.18	40.54

[1] Västmanland, [2] Södermanland, [3] Nm^3/km, [4] kWh/Nm^3.

According to the figures, the number of bioethanol vehicles in Södermanland is higher than the number of bioethanol vehicles in Västmanland. Therefore, the ethanol demand is higher in Södermanland.

As it is mentioned in the previous sections, the straw-based bioethanol production through polygeneration system is evaluated in this study. Therefore, the potential straw production in both regions is estimated using the parameters described in section 3.2.3 and the result is shown in Table 4.

Table 3 Amount of cultivated cereal straw in the studied regions [4,30,45].

	Available area (ha)		Yield (ton/ha)		Crop/ residue	Availability of straw (%)	Straw production (kton)	
	Söder.[1]	Väst.[2]	Söder.	Väst.			Söder.	Väst.
Winter wheat	27 633	19 999	7.1	7.1	1.3	0.57	145	105
Spring wheat	3 365	6 454	4.7	5.4	1.3	0.57	12	26
Winter barley	0	0	-	-	1.2	0.57	-	-
Spring barley	13 736	15 733	5.09	5.1	1.2	0.57	48	55
Oat	8 093	14 467	4.2	4.8	1.3	0.57	25	51

[1] Södermanland, [2] Västmanland.

The contribution of the renewable energy sources to energy supply are not similar in both studied regions since the availability of sources are not similar. For instance, there are only two wind farms with very low capacity in Västmanland that is basically used to provide some amount of the total power needs of local private users. Therefore, the electric power production from wind farms in this region is not considered in the model. Although the wind power production in Södermanland is greater than the wind power production in Västmanland, still the capacity of the wind farms is low. However, there are some planned projects to implement new wind power plants and increase the production capacity, in the region.

A great share of the electric power demand in both regions, especially in Västmanland, is satisfied by hydropower. Thus, the daily production profile from the local hydropower stations is added to the case study model.

The potential power supply from rooftop PV systems, which is estimated using the available area for panel installation and the regional solar radiation, is used in the model. Based on the data from SCB, there are around 56 900 and 60 000 buildings of different types in Södermanland and Västmanland, respectively [4,53]. Considering the assumption described in sections 3.3 and 3.5.1.2, a total rooftop area of around 8 km^2 and 7 km^2 would be available for panel set up in the Counties of Västmanland and Södermanland, respectively. The average solar radiation density in Västmanland and Södermanland is illustrated in Figure 3-6. As can be seen, the radiation in both regions follow a similar pattern. The radiation is high during summer and it decreases in winter. According to the weather history, 2015 was not a cold year and the temperature in wintertime was higher compared to the wintertime period in previous years.

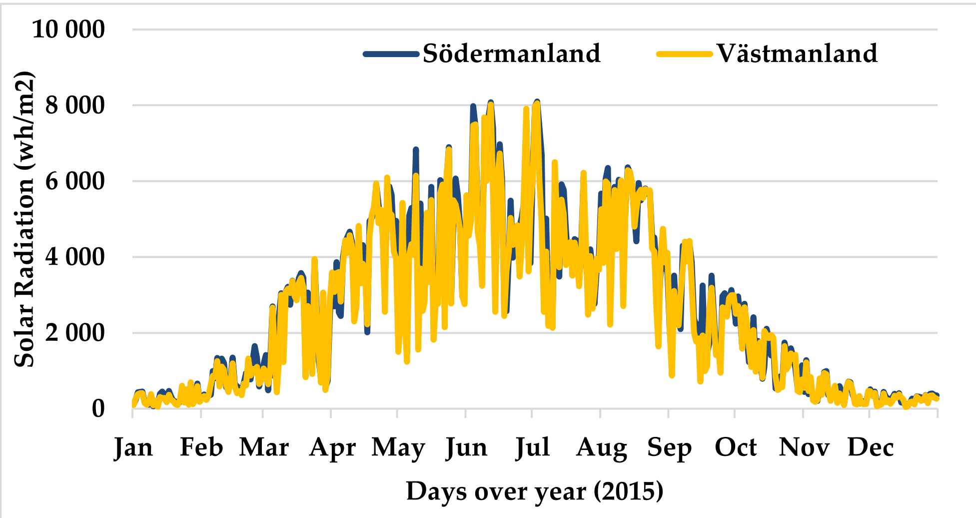

Figure 3-6 Mean solar radiation in the studied regions [56].

3.6 SCENARIOS AND SYSTEM DESCRIPTION

Future trends and behaviour in energy use, such as increased use of heat pumps or penetration of EVs could affect the demand profile, which consequently influence the operational strategy of the energy system. Therefore, such changes and extreme trends are analysed in this project through developing different optimization cases.

3.6.1 Conventional energy system

To investigate the influences of future trends in energy demand and supply on the production planning of the regional energy system, several scenarios have been developed and evaluated in this study.

In the base scenario (S0- Energy system), the PV systems defined in section 3.5.1.2 with the regional energy system including CHP plants and heat water boilers are modelled and optimized for both Västmanland and Södermanland. The demand profiles of heat and electricity in the base year 2015 are used in the optimization model in this scenario.

Due to the low operation cost and CO_2 emissions, utilization of heat pumps have been increased over time, especially in single-family houses [5]. Increasing trends in application of heat pumps to replace the district heating in the system would enhance the regional electricity use [4,64]. In addition, use of heat pumps could challenge the DH system. [5]. Therefore, the influence of reduced DH demand through using heat pumps in buildings in the energy system (with production of up to 10%, 20%, 30% of the regional heat demand) on the operational strategy of the CHP plants is evaluated in the first scenario (S1-Energy system). The target defined in the ''Increased competition on the heating market'' scenario, which is developed by Sköldberg and Rydén [5] has been used as the reference to model the case in the first scenario.

Electricity use by the heat pumps depends on several factors such as weather conditions, the size of the place where the heat pump provides energy, and the behaviour of the users. From the results of the study done by Campillo et al. [64] and the data from SCB [4], there is an increase by around 30% in electricity use of a house where heat pumps are installed as the main heating source, without any other auxiliary heat production. The same assumption is used in the first scenario to calculate the increased power demand. In addition, the assumptions are based on the application of ground-source heat pumps, since it is the mostly used type of the heat pumps in Sweden amongst other European countries [37,64,65].

The efficiency of heat pumps will be specified by Coefficient of Performance (COP) relating the output energy from the heat pumps in the form of heat to the input electricity used for heat production. In order to investigate that how the COP of the heat pumps could influence the electricity use in the system, a sensitivity analysis has been done for two different cases. In the case I, the impact of increased value of COP to 4 on the system cost and the electricity import is evaluated and in the case II the same parameters for high COP up to 5.5 is evaluated.

The use of Electrical Vehicles (EVs) in the transportation system has increased in recent years. However, the number of EVs in use in Västmanland was 58 in 2015, which corresponds to less than 1% of the total passenger cars in the region. Thus, the scenario S2 studies the increased penetration of EVs up to 10%, 50%, and 100% in the regional transportation system and evaluate the influences on the production planning of the plants in the energy system.

Application of EVs recharged with a direct power source could significantly increase the electricity use depending on the type of the vehicle and driving patterns and could be a new challenge for the energy supply for the transportation system [37]. The electricity use by EVs is estimated using equation (2) in section 3.3 and the official statistics for the number of EVs in the region, the mileage covered by the vehicle, and the average electricity use per kilometre [66].

3.6.2 Polygeneration system

The further developed polygeneration system (described in section 3.4) including the CHP plants integrated bioethanol production and potential power generation from rooftop PV system is considered to analyse the regional transportation system (see Figure 3-7). Two other cases are developed to investigate the future trends related to the transportation system and evaluate the influence of increased renewable based transport fuel production through polygeneration, on the demand and supply balance in the studied system.

- Scenario S3-Polygeneration: this scenario analyses an extreme case, where all vehicles in the transportation system except trailers and cross-country scooters are fuelled by ethanol produced from available straw.
- Scenario S4-Polygeneration: this scenario evaluates the application of hybrid vehicles in the local road traffic, so that more electricity is used in the summer period, while during winter, bioethanol will be used in the hybrid cars

In scenario S3, all vehicles including passenger cars, busses, lorries and trucks, and motorcycles are to be fuelled by straw-based bioethanol produced through a polygeneration system. Scenario S4 analyses the local transportation sector, where all vehicles are transferred to hybrid vehicles with both biofuel engines and electric motors. The intention in this scenario is to use the electrical generators during summer (almost 5 months in the year from May until end of September) when there is a high potential to generate power from rooftop solar collectors, while the straw-based bioethanol would subsequently provide the energy needs for the vehicles during wintertime. This approach could decrease the input energy use compared with the system with solely bioethanol-fuelled vehicles. The ethanol use in the proposed cases are estimated using the method described in section 3.3.

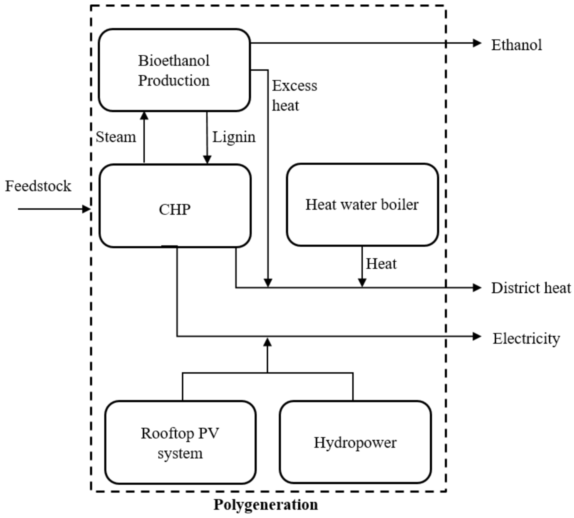

Figure 3-7 The diagram of the studied polygeneration system.

All studied scenarios are summarized below:

- Base scenario (S0-Energy system): the regional energy system in 2015 including CHP plants, heat water boilers, and hydropower, considering also the contribution from power production of rooftop PV systems.
- Scenario S1- Energy system: Increased utilization of heat pumps as the main heating source in some of the DH-based buildings in the region by a growing share of 10%, 20%, and 30% of the regional heat demand.
- Scenario S2- Energy system: Increased penetration of EVs in the studied region up to different shares of 10%, 50%, and 100%.
- Scenario S3- Polygeneration: bioethanol-fuelled vehicles in the local road traffic and providing the required amount of fuel through polygeneration system.
- Scenario S4- Polygeneration: application of hybrid vehicles, running on both electricity and bioethanol, in the regional transportation system.

The configurations of the systems defined in the studied scenarios are shown in Table 4 .

Table 4 System configurations in the studied scenarios.

		Scenarios- Energy system		**Scenarios- Polygeneration**	
Components	Base scenario	S1	S2	S3	S4
CHP plants	×	×	×	×	×
Heat water boilers	×	×	×	×	×
Hydropower	×	×	×	×	×
Solar power	×	×	×	×	×
Rooftop solar cells	×	×	×	×	×
Bioethanol production	-	-	-	×	×
Heat Pumps	-	×	-	-	-
Electrical Vehicles (EVs)	-	-	×	-	-
Bioethanol vehicles	-	-	-	×	-
Hybrid vehicles	-	-	-	-	×

4 Production planning analysis

This chapter presents the results of optimization of the different scenarios and discuss the influence of different parameters on production planning of the CHP plants and optimal utilization of different fuels. The analysis is divided into three parts considering the increased energy supply from solar energy as a renewable source, enhanced application of heat pumps and EVs in the energy system and impacts of increased use of biofuels in transportation system. Investigation of different options contributes to finding the optimal outcome concerning the cost.

4.1 INCREASED SOLAR POWER PRODUCTION

Power production using solar energy as one of the renewable energy resources could be increased through application of rooftop PV. The production profile from solar empowered system in the base scenario (S0) shows variations over the studied year due to the weather conditions and solar radiation. The power generation is obviously high during summer, when there is a lot of sunshine. However, the power supply will decrease in wintertime, so that there is no production for some days of the year.

4.1.1 Energy system in Västmanland

The results for power generation from solar collectors and CHP plants are shown in Figure 4-1 and it is compared with the electricity demand. Due to increased power generation from PV systems during summer, the production exceeds the demand. Therefore, the CHP plants in this configuration would operate at lower load and the excess power can be exported to other regions. Even though the production from solar power exceeds the demand during summer, some other power supply, for instance CHP plants, power import or storage is needed to cover the demands during nights and winter days. In general, only 19% of the power demand is satisfied by power produced by CHP plants in scenario S0. Around 35% of the annual demand in the region is met by electricity import to the region. The share of the power imports is higher in wintertime, as shown in Figure 4-1.

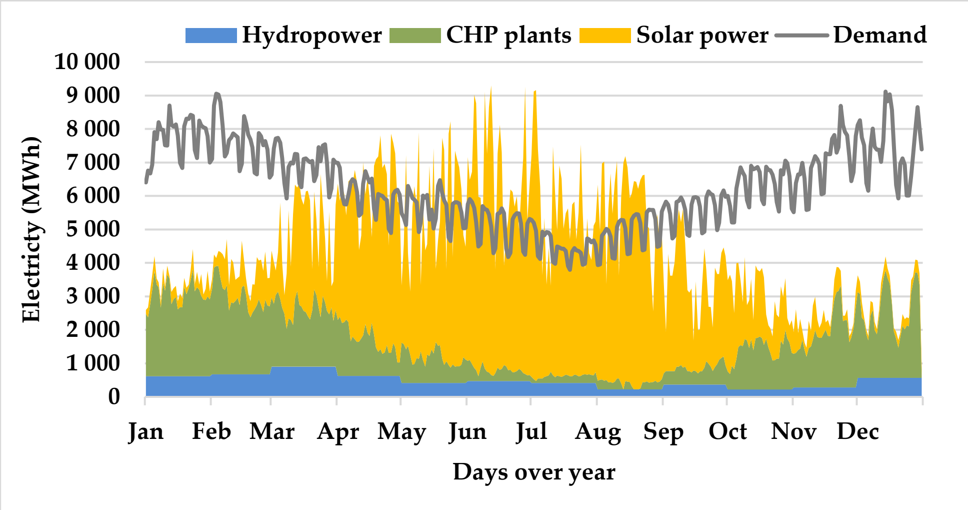

Figure 4-1 Electricity production by type of the source in the base scenario in Västmanland.

Only biomass-based plants produce heat and power in the optimized system and there is no energy supply from fossil fuels. The power and heat supply from the energy plants in the base scenario (S0) is shown in Figure 4-2. Three of the CHP plants and two of the heating plants are in operation during the studied year. However, the load of the plants is reduced during summer when the heat demand is low, and the solar power can cover the regional electricity demand. Still power supply from the plants or through power imports is needed during nights and winter. Comparing the system behaviour in the base scenario with the real-time data on plants operation in the base year reveals that with lower operation time of the plants in solar empowered scenario, the system production cost would slightly decrease. In addition, lower operation time would lead to lower emissions from plants.

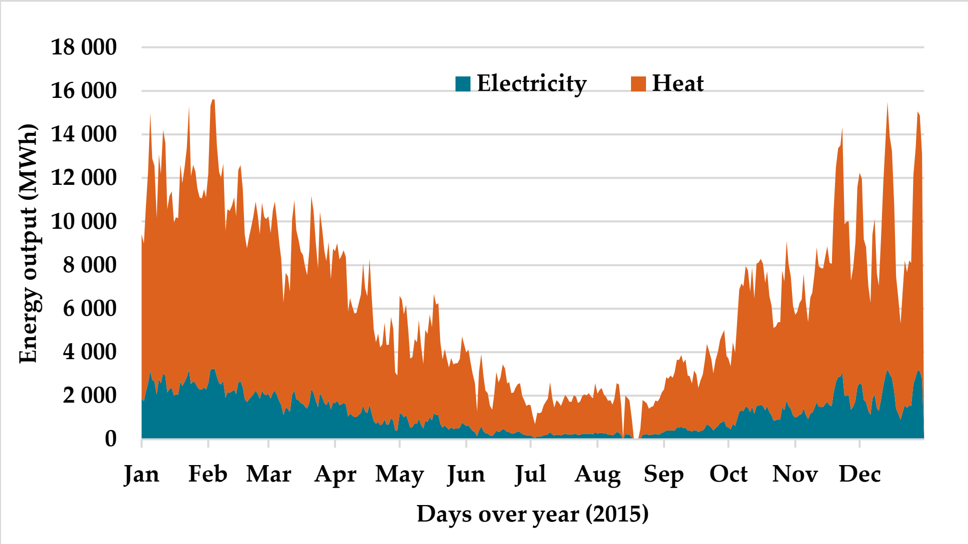

Figure 4-2 Energy outputs from the plants in Västmanland in the base scenario.

As the annual solar power production can meet around 38% of the total power needs of the region, the power imports per year would subsequently decrease in the system. However, the daily peak power import occurs in December. Based on the data from Swedish Power Grid (SVK) [67] the maximum daily power import to the County of Västmanland in 2015 was around 8 GWh. Considering this value as a reference, the maximum power import per day in scenario (S0) could decrease by around 19%.

4.1.2 Energy system in Södermanland

The electricity generation from different energy resources in the base scenario in Södermanland is shown in Figure 4-3. Due to the variations in the daily solar radiation, some fluctuations can be seen in the power production from rooftop PV system. The power generation from PV system in this region is higher for some days in the summer compared to the production in Västmanland; however, the annual solar power supply in Västmanland is around 1031 GWh, 27% more than the solar power supply in Södermanland.

Similar to the power import profile in Västmanland, the maximum power import to the region occurs in December. The peak power import per day to Södermanland in 2015 was almost the same as the maximum import in Västmanland, around 8 GWh. The power production from rooftop panels in the County of Södermanland contributes to a reduction by 11% in the maximum daily import to the region during winter.

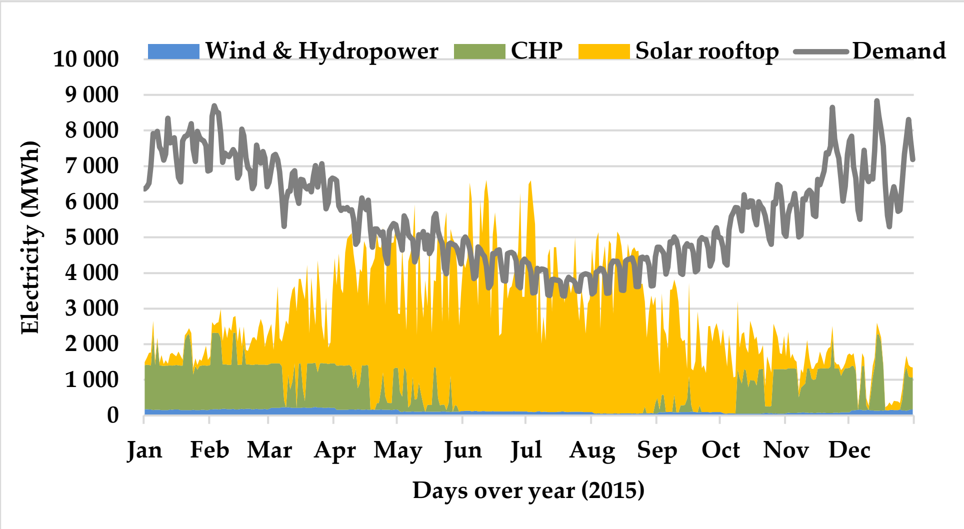

Figure 4-3 Electricity production by type of the source in the base scenario in Södermanland.

As can be seen from Figure 4-3, high solar power during summer provide some amount of the power needs. Therefore, power and heat production from CHP would decrease compared to the real-time data for the system in 2015. The energy outputs in the forms of heat and power from operating CHP plants and heat water boilers are shown in Figure 4-4.

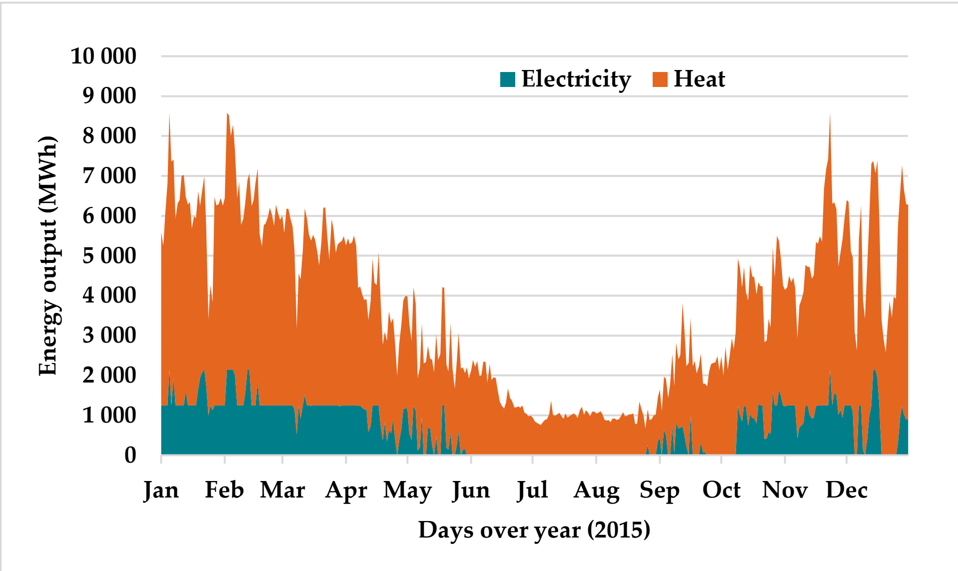

Figure 4-4 Energy outputs from the plants in Södermanland in the base scenario.

Woody biomass including wood chips and wood pellet have been used in the regional energy system. The amount of wood used as the feedstock by the energy plants in the optimized model is lower than the total amount used in the system in 2015. Comparing the wood pellet use in the optimized system with the value in 2015 shows that the wood pellet utilization has been increased. According to the optimization results, it is thus optimal to use more wood pellet than wood chips in the system.

4.2 INCREASED UTILIZATION OF EVS AND HEAT PUMPS

The main characteristic in scenarios S1 and S2- Energy system is to evaluate the impacts of electrification on system operational strategy. The result of energy balance between supply and demand shows that the increasing utilization of heat pumps, as a replacement for district heating, will reduce the amount of power and heat production from energy plants. The primary product in CHP plants is heat. Therefore, decreased district heat demand will decrease the heat production from CHP plants. Replacement of district heat with heat pumps in buildings reduces the district heat demand and consequently the heat production in CHP.

4.2.1 The County of Västmanland

Use of heat pumps, as the electrical based heating source, in the buildings, where the heating source was based on district heating, will influence both the district heat and electricity demand. As the share of the heat pump utilization increases, the output energy from plants decreases. Therefore, more electricity needs to be imported to the system in the case with 30% increase in heat pump utilization. While, less amount of fuel would be used in the system comparing to the real-time data for 2015. Three CHP plants are in operation, under the conditions defined in the first scenario. However, one of them is operating on a very low load. Total heat supply from the system described in different cases of scenario (S1) is shown in Figure 4-5.

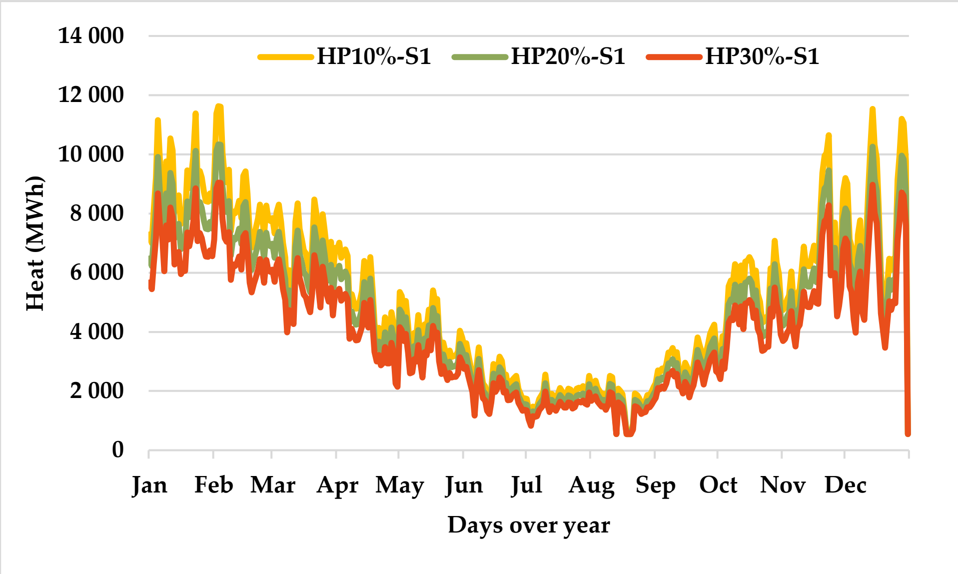

Figure 4-5 Heat production profile from the system in the first scenario (S1) in Västmanland.

Increased power demand by the heat pumps and reduced power production from the CHP plants would increase the power import. Therefore, higher share of heat pump utilization would lead to approaching the limits assigned for power import.

More penetration of EVs in the regional transportation system however does not influence the production planning of the system. The energy plants operate with the same profile as the system in the base scenario. In contrast, the electricity demand increases corresponding to the penetration of EVs in the system, which lead to higher power imports to the region. However, the annual power import in scenario S2 is less than the power import in the case with increased use of heat pumps (S1). The optimization results for scenario S1 and S2- energy system is compared and shown in Table 5.

Table 5 Optimization results of the system in Västmanland in different scenarios.

(GWh/year)	Base scenario	Heat pump Scenario S1			EVs Scenario S2		
		10%	20%	30%	10%	50%	100%
Electricity supply-PV system	1 033	1 033	1 033	1 033	1 033	1 033	1 033
Electricity supply-hydropower	176	176	176	176	176	176	176
Electricity supply-CHP plants	441	381	330	262	441	441	441
Electricity Imports	795	901	1 010	1 119	817	907	1 026
Electricity demand	2 278	2 346	2 414	2 483	2 430	2 553	2 708
District heat supply	2115	1 903	1 692	1 408	2 115	2 115	2 115
District heat demand	2 115	1 903	1 692	1 408	2 115	2 115	2 115

4.2.2 The County of Södermanland

Similar operation results can be seen for the energy system in Södermanland. The modelling results for different cases are shown in Table 6.

Table 6 Optimization results of the system in Södermanland in different scenarios.

(GWh/year)	Base scenario	Heat pump Scenario S1			EVs Scenario S2		
		10%	20%	30%	10%	50%	100%
Electricity supply-PV system	798	798	798	798	798	798	798
Electricity supply-wind and hydropower	45	45	45	45	45	45	45
Electricity supply-CHP plants	253	237	219	198	254	258	260
Electricity Imports	1 025	1 098	1 171	1 248	1 050	1 150	1 282
Electricity demand	2 047	2 108	2 170	2 230	2 077	2 195	2 344
District heat supply	1 105	995	884	774	1 105	1 105	1 105
District heat demand	1 105	995	884	774	1 105	1 105	1 105

The behaviour of the system in the cases with increased use of heat pumps is similar to the system operation in Västmanland. A difference can be seen for the case that the EVs penetration increases in the system in Södermanland. As the electricity use increases in scenario S2, the power supply from CHP plants slightly grows. Still, the increased power production would not satisfy the high demand in the system (only around 10% of the total power demand in the region) and a great share of power needs is met by import. The power generated from rooftop PV systems could provide a great share (around 35% in Västmanland and 33%, in the case with 100% EVs in Södermanland) of the annual power needs; however, in wintertime, import of electricity from outside the region is necessary.

Comparing the energy supply results in this County with the amount of energy supply in Västmanland, under the conditions in scenarios S1 and S2, indicates that the energy supply from the system in Södermanland is lower than the total supply in Västmanland. This would consequently increase the import to region.

The maximum power import per day in 2015 for each region is used as the limitation reference. The case with the highest power import approaching the limit assigned for each of the regions would cause problems according to the restrictions in the regional power grid. Although the power imports in the developed scenario are below the limits per day, there might be the capacity problem to import electricity during some hours in peak demand days.

In all scenarios, electricity is imported to the system. However, the extreme case in the second scenario has the highest power imports compared to the other analysed scenarios in the County of Södermanland. Hence, regional transmission network for electricity import and restrictions on the grid should be recognized and evaluated.

According to the statistics from SVK[1], the maximum amount of electricity that has been imported to the region in 2015 was around 8 GWh per day. Given this value as an upper limit for the transmission system, increased power imports in the second scenario could approach the import limit assumed for the regional grid. The maximum electricity import in this scenario is around 7.5 GWh per day, which could be close to the grid capacity. Therefore, higher electricity demand could cause a problem concerning the power import and providing the energy needs in the region.

4.2.3 Sensitivity analysis regarding COP of heat pumps

Based on the assumptions in the first scenario, the value for COP is basically between 2 to around 4. The variation in the COP is due to the changes in the outside temperature. During the cold weather, the heat pumps need to work on the highest power to provide the required amount of heat. Amongst different types of heat pumps, air-source heat pumps are more sensitive to the temperature, however, the sensitivity for ground-source heat pumps are lower as the temperature under-ground does not change so much, by the outside temperature. Thus, the COP of the latter type does not fluctuate a lot over the year.

Increased COP will decrease the electricity use by the pump. A sensitivity analysis for the studied cases shows that the higher efficiency of the heat pumps would slightly influence the total electricity import. By increasing the value of COP, the power import will be reduced by 2%, 4%, and 6% in the different cases in scenario S1 with 10%, 20% and 30% of increased heat pumps use. The system production cost will also decrease; however, the reduction is less than 1% in all cases. Therefore, the system has a low sensitivity to the efficiency of heat pumps.

4.3 INCREASED BIOFUEL USE IN TRANSPORATION SYSTEM

The transportation system in Västmanland is used as the case for this part of the study.

Based on the reported data from SCB, around 7 000 vehicles run on ethanol in 2015 in the County of Västmanland. The estimated cereal straw production in the region (Table 4) and the energy content of the straw show that there is a potential for local production of around 950 GWh straw-based bioethanol. However, considering the conversion ratio of straw to bioethanol at ethanol plants, only 28% of the estimated potential bioethanol supply can be produced, which could not provide the required amount of bioethanol in the region.

The optimization results for the studied polygeneration system in scenarios S3 and S4 are shown in Table 7. Total bioethanol supply in the third scenario, where an extreme case for use of bioethanol is developed, indicates that the available straw in the region is not sufficient to cover the fuel needs of the extreme case. The overall system efficiency in the polygeneration design is higher than the production efficiency in the stand-alone bioethanol plant. Based on the results for total energy supply from scenario S3, integration of the ethanol production with

1 E-post communication with Swedish Power Grid company (Svenska Kraftnät AB)

existing CHP plants could increase the heat and power supply. However, there is a lack of bioethanol production.

In order to meet the bioethanol demand in the transportation system described in S3, either bioethanol or cereal straw needs to be imported to the region. The cost of importing straw and bioethanol is compared in Table 7. The results reveal that a great amount of straw need to be imported to meet the lack of the bioethanol production, which increase the system cost by around 381 MSEK. Considering the energy conversion ratio of straw at bioethanol plants, import of the equivalent amount of bioethanol that can be produced by the imported straw, would result in a cost increase by 2 878 MSEK. Therefore, it is more cost effective to import cereal straw than bioethanol to the region to meet the demand.

The amount of straw in the region could be increased through increased cultivation of cereal. This would be done using the available fallow land in the region. According to the statistics from Swedish Agricultural Board, around 13% of the total arable land in Västmanland accounts for fallow land. Utilization of fallow land for cereal cultivation would increase the bioethanol supply by around 23% up to 326 GWh per year, which is still not sufficient to meet the demand.

Other type of biofuel can be used as the transport fuel. According to the data in Table 3, around 34% of the busses used in the regional transportation sector in Västmanland are fuelled by biogas. Considering all busses fuelled with biogas in the transportation sector, the daily bioethanol demand would slightly decrease by 4%.

The system in scenario S4 is a combination of the system described in scenarios S2 and S3, where all vehicles are of hybrids type, fuelled with straw-based bioethanol and electricity. This is an approach to decrease the bioethanol demand in scenario S3 and reduce the power needs in scenario S2. The hybrid vehicles in the system, developed in scenario S4, use straw-based bioethanol during winter. Whereas, in summer, electricity generation from the plants and the proposed rooftop solar cells can provide the energy for the vehicles.

The energy plants in the system in scenario S4 can produce 627 GWh power, 1 908 GWh heat, and 1 147 GWh bioethanol per year. Due to utilization of bioethanol as the transport fuel during winter days, the straw use would also be reduced compared to scenario S3. Despite the lower utilization of cereal straw, it is still higher than the locally cultivated amount. With application of fallow land, the available straw could provide approximately 30% of the total energy needs. Therefore, the lack of production needs to be covered by import of straw.

The conversion ratio of the overall feedstock to the energy outputs is 61% in this system, which is higher than the overall efficiency of the system in scenario S3.

Table 7 Modelling results for scenarios developed for polygeneration system.

	Scenario S3	Scenario S4
Description	Transportation system with bioethanol-driven vehicles	Transportation system with hybrid vehicles
Heat production from plants (GWh/year)	1 962	1 908
Power production from plants (GWh/year)	725	627
Available straw (kton/year)	237	237
Used straw (kton/year)	1 763	1 024
Bioethanol demand (GWh/year)	1 975	1 147
Bioethanol production (GWh/year)	1 975	1 147
Bioethanol import (MWh/year)	0	0
Power demand (GWh/year)	2 278	2 485
Total power production including solar & hydropower (GWh/year)	1 933	1 836
Total power import (GWh/year)	588	724
Maximum power import per day (GWh/day)	5.5	5.5
System efficiency (%)	54%	61%
Increase in cost due to straw import (MSEK/year)	381	197
Increase in cost if ethanol is imported (MSEK/year)	2 878	1 475

The primary product for the CHP plants in the system is heat and the bioethanol production is based on the variations in bioethanol demand during the year. Results for plants operation show that only 10 of the 39 plants are in operation in the system in the third and fourth scenarios. Total energy output in the forms of heat, power, and bioethanol produced from the operating plants in the system by type of the plant is shown in Figure 4-6 and Figure 4-7 for scenarios S3 and S4. The conversion of maximum available straw in the region, excluding the use of fallow land in straw production, and the imported straw to the plants is considered in the system.

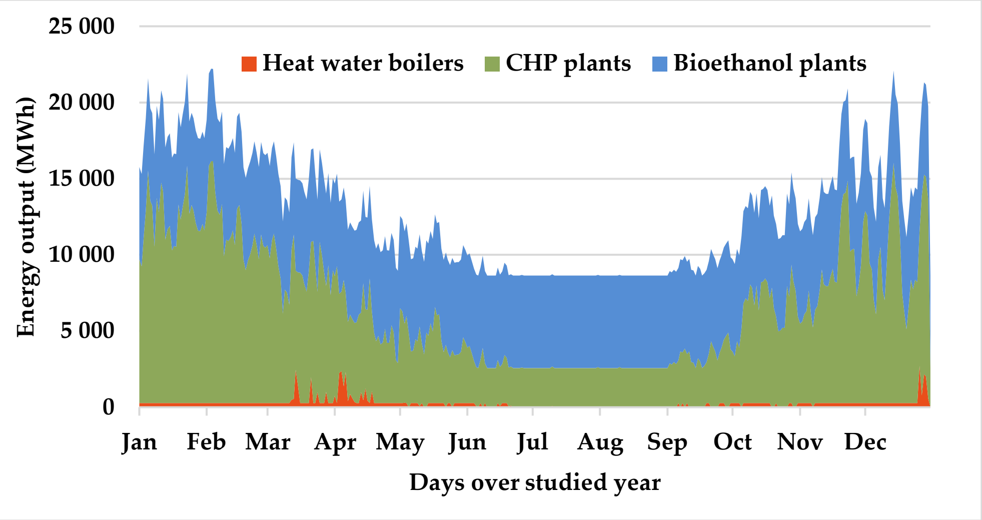

Figure 4-6 Energy outputs from different plants in the energy system in scenario S3.

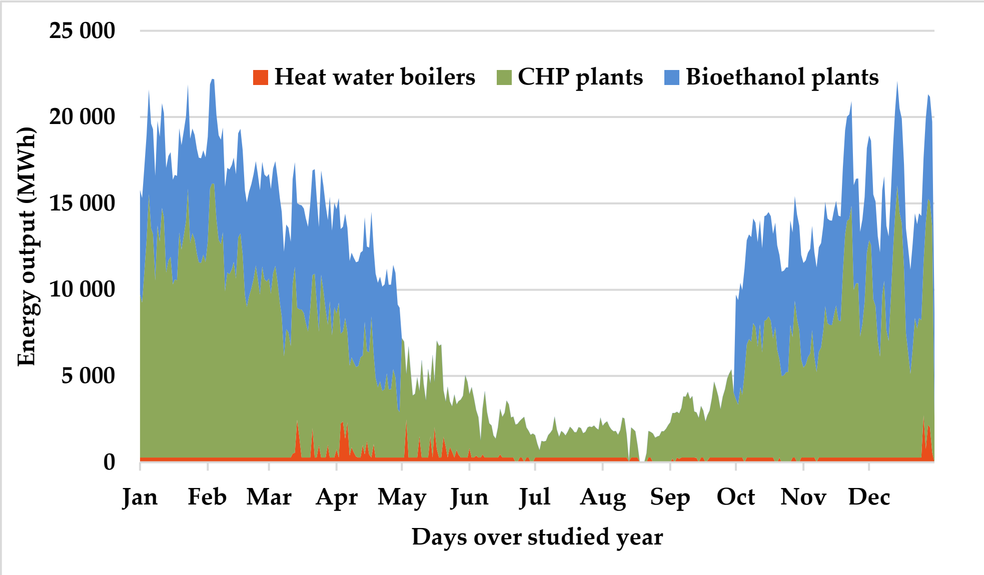

Figure 4-7 Energy output from different plants in the system in scenario S4.

Plants operation profile in scenario S3 shows that all bioethanol plants are in operation during the entire studied period due to the high bioethanol demand in the system. The excess heat from bioethanol plant can be used in the district heat network, therefore, the CHP plants and heat water boilers would operate on lower loads for some days over the year. However, the by-products from bioethanol production processes are used as the input fuel in the CHP plants; thus, the production of the CHP plants in the system increases, compared to the base scenario where biomass-based fuels are used in CHP plants.

Owing to use of electric power as the primary fuel in hybrid vehicles in summer, the bioethanol plants in scenario S4 are shut down during this period. The production of heating plants increases in the same period, compared to the system in the third scenario. Moreover, the overall energy supply from the CHP plants slightly increases, compared to scenario S3, to meet the regional district heat demand, especially during summer. The difference in CHP plants operation can be seen from Figure 4-6 and Figure 4-7. The CHP plants in the scenario S3 mostly use the by-products from bioethanol plants to produce heat and power, while in scenario S4, where there is no by-products during summer, more biomass-based fuels such as municipal waste and wood will be used in the plants.

Production profiles during cold days of the year show that most of the energy plants in the system are in operation, as the heat demand is higher during wintertime. Some fluctuations can be seen in the production pattern from CHP plants in the system described in scenario S3.

The production of bioethanol in the polygeneration system increases the electricity production from CHP plants. Thus, the power import can be reduced in the integrated system, compared to the base case. In scenario S4, the hybrid vehicles are fuelled by electricity during summertime; therefore, the electricity demand will increase in the region. The CHP plants together with power production from hydropower and rooftop PV systems provide the electric power for the vehicles.

However, the production is not high enough to meet the demand and a proportion, around 30%, of the annual power demand in the region, is satisfied by power imports.

The balance between production and demand in the system in all studied cases shows that some amount of electric power is exported to other regions. There is also excess heat from the plants in some of the studied cases. The amount of extra heat production and the exported power in the extreme scenarios and the base scenario are shown in Table 8.

Table 8 Exported heat and power in different scenarios.

	Base Scenario		S1-HP30%		S2-EV100%		S3	S4
(GWh/year)	Väst.[1]	Söder.[2]	Väst.	Söder.	Väst.	Söder.	Väst.	Väst.
Power Export	166	55	107	38	89	21	242	75
Extra Heat	0.1	0	0.7	0	0.1	0	54	0.1

[1] Västmanland, [2] Södermanland.

There is no excess heat from the system in Södermanland. The amount of extra heat production from the polygeneration system in scenario S3 has the highest value amongst other cases. It is possible to store the extra heat in the storage tank for couple of hours or even some days. However, the large amount of excess heat produced in scenarios S3 could not be used in a short term. Therefore, the seasonal heat storage needs be applied in such cases. For this, new underground thermal storage technology could be applied, which might be expensive and with some heat losses. There is a giant underground heat storage in the city of Vojens in Denmark, which operates as the inter-seasonal thermal storage [68,69]. Another underground storage system is used in Canada to store large quantities of the solar heat during extra production in summer [70]. Application of such structure for heat storage in the studied region might be possible in the far future. Therefore, there would be some problems in using the excess heat produced by the system, especially in scenario S3.

Scenario S2 with 100% penetration of EVs has the lowest power export, since the electricity use by the vehicles is high in this case. Hence, most of the generated power is used in the regional system and lower share is exported to other region, comparing with the power export in other cases. The power export obviously occurs in summer because of the increased power supply from PV systems.

4.4 CO_2 EMISSIONS

CO_2 emissions from the energy plants in different scenarios vary over the studied year, based on the amount and type of the used fuels. Total CO_2 emissions from energy systems in different scenarios including fossil-based and biomass-origin emissions are show in Figure 4-8.

The system with 30% increase in heat pumps utilization has the lowest emissions since the operation of the energy plants decreases. A large part of the emissions from energy system is of biomass-based type as only biomass–based fuels are used in the system. However, some share of the municipal wastes used in Västmanland contains fossil-based material that would release fossil-origin CO_2 to the environment. The share of fossil-based emissions is different in each scenario in the counties of Västmanland and Södermanland. Since the municipal waste is not used in the system in Södermanland, there is no fossil-based emission from the system in this region.

However, more that 40% of total CO_2 emissions in scenarios S1 and S2, which are developed for Västmanland, is fossil-based emissions. The high share might be due to the utilization of higher amount of municipal wastes than other fuels in the system. The share can slightly decrease for the case with 10% raise in heat pump utilization. The fossil-based emissions in the second scenario with increased use of EVs is the same as the emissions in the base scenario. It has also the highest fossil-based emissions amongst all scenarios, due to the high amount of fuels used in the energy system compared to the first scenario.

By integrating bioethanol production to the CHP plants, total emissions will sharply increase due to utilization of straw as the fuel for bioethanol supply. However, the system has low share of fossil-based emissions, with less than 10% of total CO_2 emissions. The emissions profile in wintertime in scenario S4 is high, like the emissions in the third scenario. During summer in scenario S4, when bioethanol is not produced, the emissions will subsequently be reduced. The share of the fossil emissions in this scenario is between the emissions in scenarios S2 and S3, around 10% of total emissions.

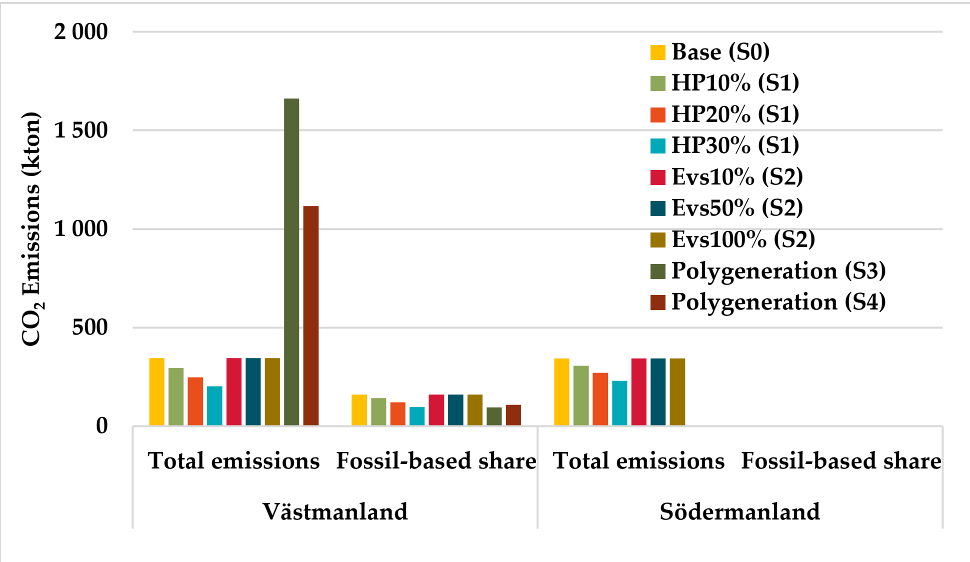

Figure 4-8 CO_2 emissions by source of the emission in the studied regions.

According to the emissions from the energy plants in Västmanland and Södermanland, shown in the figure, the emission in Södermanland is slightly lower in some scenarios. There are more energy plants with higher capacity in Västmanland; therefore, the amount of used fuels would be higher in this region compared to the system in Södermanland. This will consequently increase the emissions from the system.

The marginal CO_2 emissions regarding the power imports is calculated in the model, based on the assumptions described in section 3.2.1. In general, the marginal emissions in Södermanland is higher than in Västmanland. The results show that the system with lower power import has the lower marginal CO_2 emissions. For instance, the heat supply from the CHP plants will decrease through replacement of heat pumps with district heating in the system. With lower heat supply, electricity generation will also decrease. Thus, higher amounts of power demand needs to be covered by the import, which will subsequently result in the higher marginal CO_2 emission compared to the emissions in other scenarios. The base scenario has the lowest marginal emissions amongst other studied cases. The modelling result for marginal CO_2 emissions is shown in Figure 4-9.

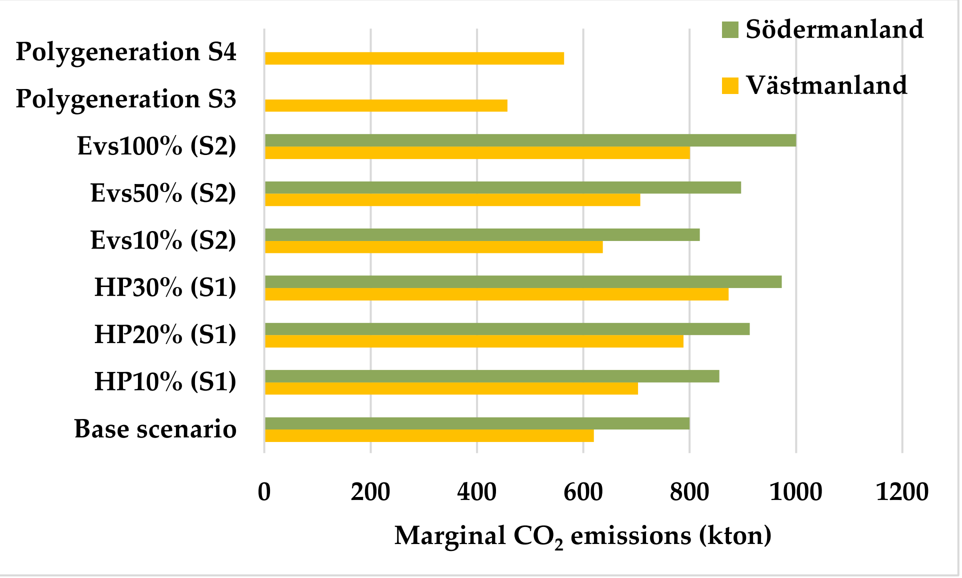

Figure 4-9 Marginal CO_2 emissions in different scenarios.

4.5 OPTIMAL OPTION

To find the optimal system, the optimization results for extreme cases in scenarios S1 and S2 are compared to the results from the polygeneration scenarios S3 and S4, concerning the key parameters including the system efficiency, fuel use or import, power import, and CO_2 emissions. The summary of results is shown in Table 9.

Table 9 Comparison of different parameters in the developed scenarios.

	Base scenario		S1 (HP30%)		S2 (EVs 100%)		S3	S4
	Väst.	Söder.	Väst.	Söder.	Väst.	Söder.	Väst.	Väst.
Used straw (kton/year)	-	-	-	-	-	-	1 763	1 024
Straw import (kton/year)	-	-	-	-	-	-	1 526	787

	Base scenario		**S1 (HP30%)**		**S2 (EVs 100%)**		**S3**	**S4**
Biomass-base fuels incl. municipal waste(kton/year)	538	389	311	275	538	391	374	435
Fossil-based fuels (ton/year)	0	0	0	0	0	0	0	0
Max power import (GWh/day)	6.5	6.9	7.4	8.3	7.3	7.7	5.5	5.5
CO_2 emissions (kton of CO_2/year)	345	343	203	230	345	343	1 661	1 116
Fossil-based emissions (kton of CO_2)	160	0	97	0	160	0	95	108
Production Cost ($\times 10^6$ SEK/year)	17 143	17 175	17 100	17 156	17 190	17 230	17 950	17 620

To decide on the optimal case, all scenarios have been compared in terms of power import, fuel use, system production cost, and emissions.

According to the optimization results, total power imports in the first scenario (S1) is generally higher than the imports in the second scenario (S2) except the case with 100% penetration of EVs in Södermanland. The peak daily power import is almost the same for both scenarios (see Table 9) approaching the daily import limit to the region, which is assumed to be 8 GWh. However, the maximum power import per day in the second scenario in Södermanland (with 30% increase in HP utilization) is high and it is slightly more than the daily limit.

As can be seen from the table, the power import will significantly decrease in the polygeneration system (scenarios S3 and S4). According to the reports confirmed by Swedish Power Grid authority [71], there are shortcomings in the capacity of transmission lines for electricity import and power supply in the region. Therefore, proposed systems in the last two scenarios, compared to systems in S1 and S2, can be the optimal case concerning the power import.

Considering CO_2 emissions, the first scenario with 30% increase in heat pump application in Västmanland has low fossil-based CO_2 emissions compared to the base scenario and other studied cases. Conversely, the marginal CO_2 emission due to the power imports is the highest in this scenario. The production cost of the system in this scenario is also low as the operation of plants decreases through using heat pumps. The fossil-based emissions in the polygeneration system under the third scenario is also low; however, the system cost is very high since most of the straw used in the system is imported.

A large share of the system cost in different cases is due to panel installation. According to the results for the production costs in different scenarios, as the energy supply from plants decreases (for example, S1-HP30%), the production cost will also reduce. While, higher production will consequently increase the cost (system in S2-EV100% and S3, for instance). In fact, high demand would lead to the increased load of the CHP plants and fuel use and import as well as products import. Therefore, the system cost, which includes the cost of energy conversions, fuel production and import cost, and the cost for product imports, will increase.

Evaluating the fuel used in each case shows that increased heat production from heat pumps would influence the fuel use. According to the results in Table 9, utilization of biomass-based fuels has been reduced in the second scenario. In addition, polygeneration design in scenario S3 with straw-based bioethanol production could significantly affect the biomass-based fuel use in CHP plants. As can be seen from the figures, the maximum amount of input fuels including straw is used in scenario S3. Without considering straw, low amount of biomass-based fuels, especially municipal wastes, is used in the CHP plants in this scenario, as the by-products from bioethanol plants can be used in the plants to produce heat and power. This results in lower fossil-based CO_2 emissions, compared to the base scenario.

Comparing the polygeneration system suggested in scenario S3 and S4, the overall energy efficiency is higher in scenario S4. Through integration of bioethanol production with CHP plants in the region, the electricity supply will be increased that slightly reduces the need for power imports. The available cereal straw in the region could not meet the bioethanol demand for replacement of all vehicles in the region with bioethanol cars. A great share of the required straw needs to be imported. However, application of hybrid vehicles in the transportation system with use of both electricity and bioethanol as transport fuels could decrease the imports as well as the system cost compared to scenario S3.

As can be seen in the comparison summary in Table 9 and the optimization results, increased heat production through more utilization of heat pumps in the system would be the optimal option concerning the system cost, total fuel use and total CO_2 emissions from energy plants. Whereas, it has the high level of marginal CO_2 emission as the power import is high in this scenario. The polygeneration design of the system leads to reduced power import. Therefore, marginal emissions are reduced in scenario three and four.

Between the two scenarios of polygeneration system, scenario S4 with increased hybrid vehicles in the transportation system has less system cost. Hence, from imports point of view and considering the system cost, the system defined in the last scenario seems to be the optimal case. Moreover, the fossil-based emission is lower than the emissions in the base scenario and scenario S2.

5 Conclusions

In this study, an energy system including regional CHP plants and heat water boilers with interaction with local renewable resources, solar, wind, and hydropower, is studied with the scope of evaluating the influence of different parameters on production planning of energy plants. The system is further integrated with bioethanol production from available cereal straw in the region. Different optimization cases are modelled and analysed to find the optimal production strategy of CHP plants concerning the availability of resources, fuel use, CO_2 emissions, and trends in energy demand and supply.

The main conclusions of the study related to the key objectives are summarized below:

- **Increased energy supply from renewable resources**

With increased power production from suggested rooftop PV system in this study, the operation time of the CHP plants decreases and there might be no need to run the CHP plants during summer. Therefore, fuel use will consequently decrease comparing to the fuel use in the stand-alone CHP plants. Moreover, the overall power imports per year will decrease. Still there might be capacity issue regarding the power imports per day or hour during winter days.

- **Possible extreme optimization cases for the energy system**

Increase in heat pump utilization as the main heating source in single-family houses (based on the target that is set in [5]) will further increase the shut off time of the heating plants. Providing heat demand for some of the consumers will reduce the district heat demand. Thus, the heat supply from CHP plants will be reduced by 10% to 28% compared to the base scenario, depending on the increased share of heat pump use. This would sharply affect the fuel use in the system and less feedstock with a reduction of up to 28% (for the extreme case in scenario S1) will be used in energy conversion process in the system, which could subsequently reduce total CO_2 emissions from the plants by 36%.

As an electrical-based heating source, more application of heat pumps in in DH-based buildings will increase the electricity use. Since the operation time and power supply from CHP plants decrease in the system, the higher value of power needs to be imported to the region.

Another extreme situation is analysed where EVs are used with 100% penetration in the regional transportation system. The main finding in this scenario is that the power demand will significantly be, while there is no sharp changes in fuel use and the heat load of the CHP plants compared to the base scenario. The amount of used fuels in the energy plants are almost the same as the amount used in the base scenario. Therefore, CO_2 emission from the energy plants is not affected by this scenario.

The fossil-origin emissions account for more than 40% of total CO_2 emission from the systems in the extreme cases, almost similar to the share in the base case. The power generation from rooftop PV panels could meet part of the electricity need during summer. Nevertheless, the daily power import will be increased up to 7.5 GWh, which approaches the capacity of the transmission line.

The marginal CO_2 emission is related to the power import. Therefore, greater import of electricity will lead to upper marginal CO_2 emissions. Comparing the marginal emissions in the studied regions, the emission is higher in Södermanland as the power import is higher in this region. According to the optimization results for different scenarios, the extreme case with 30% heat pump and 100% penetration of EVs have the highest amount of the marginal emissions amongst all studied cases, by an increase up to around 40% compared to the base scenario (that is occurred in S2-HP30% in Västmanland).

- **Polygeneration design and transportation system**

A polygeneration design is applied to the studied system by including the bioethanol production from the locally cultivated straw integrated with existing CHP plants. The results from the current study show that the optimal approach is not only dependent on the system cost.

According to the findings from optimization model, integration of bioethanol with CHP plants can increase the total heat and power supply in the system. Hence, the power import per day will be lowered by around 20% through integrated production, compared to the import in the base scenario. Utilization of input biomass-based fuels will be reduced; while, the plants operation time is less affected by the integration since the by-products from bioethanol plants are used as the extra feedstock to the CHP plants. The excess heat from processes in bioethanol production is also added to the district heat network.

The evaluation of the developed scenarios for polygeneration system reveals that application of hybrid vehicles in the regional transportation system is the optimal approach concerning key parameters such as energy efficiency, straw use, total CO_2 emissions and total production cost. There is lower necessity to import cereal straw to the region (due to a reduction by 42% in total straw use) compared to the scenario S3, where all vehicles in the regional transportation system are to be fuelled with bioethanol. Therefore, the production cost of the system is lower in the scenario with hybrid vehicles.

Evaluation of each scenario shows that the applications of heat pumps and the polygeneration strategy with use of hybrid vehicles in transportation systems will influence the production planning of CHP plants. Developed optimization models can be applied to other energy systems considering the availability of resources to increase the knowledge of production planning and the impacts of integrated renewable energy sources.

6 Future work and recommendations

Further extension of the project is possible considering the results of the current work.

The potential increased production of solar power through installation of rooftop PV systems is studied in this study. The potential power generation from wind power plants could be estimated and used in the model in future studies. The potential power supply from new wind farms could be estimated based on the new projects on implementing new plants or increased capacity of existing wind farms in the near future in each County.

Due to the increased changes from using DH to application of heat pumps, especially in single-family houses, the influence of increased utilization of heat pumps, as a replacement of DH, is investigated in this study. However, transferring from utilization of direct-electricity heating source to heat pumps would also influence the energy system by reducing the electric power use, which can be studied in the future work.

As shown in the result of the study, integration strategy and polygeneration design of a conventional energy system could increase the heat and power supply in the system. However, the efficiency of the bioethanol conversion is low. As a possible way to increase the efficiency, other energy conversion technologies such as gasification and pyrolysis can be applied to produce other type of biofuels like biogas, HVO biodiesel, and methanol that can be used as transport fuels.

Another solution might be use of other type of biomass, which has high productivity with low input energy requirements for cultivation and treatment before conversion processes. Cellulosic energy crops, as an example, have high yield meaning that they can grow in bad conditions of weather or soil with low energy needs for cultivation. With lower energy input in biomass production and high production yield, the land use to supply a certain amount of biofuel will slightly decrease [72].

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Appendix A: Model input data

In this appendix the input data used in the regional energy system model and the sources used to collect the data are described.

In Table A- 1, all parameters used in the regional energy model and the sources used to find data for the simulation are given.

Table A- 1 Model parameters and the reference of the collected data.

Parameter	Unit	Ref.
Energy system		
Available fuel at the plant	ton	Real-time data from energy companies (direct communication)
Fuel price (production/Import)	SEK/ton	Real-time data from energy companies (direct communication)
District heat demand	MWh/day	Calculated based on the data from energy companies
Power demand	MWh/day	SVK [67] (direct communication)
Plants capacity	MW	Real-time data energy companies, [47]
Energy conversion cost	SEK/MWh	Data from energy companies (the same cost for similar fuel used at different plants)
Electricity price	SEK/MWh	[73]
Heat market price	SEK/MWh	[74], data from energy companies
Emission factor of fuels	ton CO_2/ton fuel	Data from energy companies
Power-to-heat ratio	-	Real-time data from energy companies
Available waste heat	MWh	Data from energy companies, [75]
Max. Power Import	MWh/day	Calculated based on the data from SVK (direct communication)
Electricity use by heat pumps	MWh	[4,64,76]
Renewable resources		
Hydropower capacity (power supply)	MW (MWh/day)	Data from energy companies Mälarenergi AB, Nyköping Vattenkraft (Email communication), [48]
Solar power production (available)	MWh/day	[46,67]
Number and type of buildings	-	Calculated based on the QGIS data from Västerås Municipality, [4]
Available area for rooftop PV panels	m^2	Estimated based on data from Västerås Municipality, [4]
Solar radiation density	Wh/m^2	[54]
Panel installation cost	SEK/W_{peak}	[56]

Energiforsk

Parameter	Unit	Ref.
Operation and maintenance cost rate of PV system	-	[56]
Depreciation rate (salvage value for PV system)	_ (SEK)	[57]
Transportation system (polygeneration)		
Number of vehicles by type	-	[4,8]
Transport fuel demands	MWh/day	Estimated based on [4,13,16]
Bioethanol price	MWh/day	[77]
Available cultivation area (straw production)	km^2 (ton)	[4,16,30,45]
Straw production cost	SEK/ton	[16]
Imported straw price	SEK/ton	[16]
Ethanol plant capacity	MW	Calculated based on [13]
Heat-to-ethanol ratio (at ethanol plant)	-	Calculated based on [13,16]
Power-to-ethanol ratio (at ethanol plant)	-	Calculated based on [13,16]
Ethanol-to-inlet fuel ratio	MWh ethanol/ton of fuel	Calculated based on [13]

Energy system

The real-time data from the energy companies Mälarenergi and Eskilstuna Energi och Miljö, which owns most of the energy plants in Västmanland and Södermanland, are used to find and/or estimate most of the input data for modelling including the capacity of plants, type and the amount of input fuels, conversion cost, and the conversion ratio. The Swedish Energy Agency (SEA) databases together with Statistics Sweden (SCB) [4] have been utilized to collect general and regional statistics including population in the Counties, district heat demand, and total power by type of the production source and district heat supply in the base year of the study. Nordpool daily electricity price in 2015 [73] and monthly DH selling price provided by the energy companies are used in the model. To find the transport fuel price, the statistics on bioethanol selling price in 2015 reported by an oil and energy company in Sweden are used [77].

Due to the lack of data on daily basis (the modelling resolution), the daily variations of some of the input data for modelling, like heat demand, are estimated using the available daily data at smaller scale, like a city, which are scaled up to the County level.

CO_2 emissions calculations are done using the emission factor of each fuel (in ton of CO_2 / ton of used fuel) from the real-time data from energy companies and total amount of each fuel used in different energy plants. The marginal fossil-based CO_2 emissions from importing electricity, in terms of ton of CO_2 per MWh of imported power, are included in the calculations. The marginal emission factor in 2016, 0.78 ton CO_2/MWh power, estimated by [52] has been used.

Renewable energy resources

Daily power production from hydropower and the capacity of each station are provided by the owner of some of the plants through direct contact and/or the capacity of each station from available reports [47].

Regional statistics by SCB, direct communication with the authority for the Swedish power grid network [67] and the available statistics from the owner companies [46] are used to collect data for the existing solar and hydropower plants.

To estimate the potential solar power production from rooftop installations, the number of buildings and available areas, a QGIS geographical map provided by the Municipality authorities and the statistics in SCB have been applied [53]. The available area for solar collector installation varies depending on the type of the building, which is divided into multi-family houses, single-family houses, and public buildings.

Data regarding the sun position and solar radiation is found from the databases provided by Swedish Meteorological and hydrological Institute (SMHI) using the latitude and longitude of each city in the studied region [54]. Solar Panel specifications are also assumed to be the same as the characteristics of the panels in the existing solar park in Västmanland County.

Transportation system

Databases from Swedish Energy Agency, Statistics Sweden (SCB), and Swedish Transport Agency [4,8,59,66] are used to estimate and/or find statistics for current situation of the transportation system, the number of vehicles in each region, average distances in km driven by each type of the vehicle, and the fuel use.

In [58] the number of the busses and trucks in each County that are run on biogas is given. The type of the fuels used in the rest of the trucks and busses have not been found, however, it is assumed that they are fuelled by diesel. All motorcycles are considered as petrol fuelled vehicles.

Input data for calculation of straw-based bioethanol production, integrated with CHP plant in a polygeneration design, are collected from statistics about the cultivation areas and the harvest yield of the cereals in each studied region found in databases provided by Swedish Agricultural Board [45]. The relation between straw as residues and the cultivated cereals is found from the previous studied and related literatures [13]. In order to prevent the soil erosion and maintain its productivity, a share of the residues or straw has to be ploughed into the land. The same share of available straw for energy purpose used by [22,30] is used in this study.

Appendix B: Characteristics of energy plants

In this appendix the characteristics of the CHP plants and heat water boilers in the modelled regions are listed, see Table B- 1.

Table B- 1 Specifications of energy plants in 2015, [4,47,75,78] **used as input in the optimization model.**

Type of the plant	Plant location	Fuel type	Installed Capacity (MW)	Type of the plant	Plant location	Fuel type	Installed Capacity (MW)
CHP	Väst.[1]	Tall oil, coal, Fossil oil	165	Heating Plant	Väst.	Municipal Waste	11.5
CHP	Väst.	Tall oil, Coal, Fossil oil	165	Heating Plant	Väst.	Bio-oil	46
CHP	Väst.	Biomass-based fuel, Wood chips, Peat, Tall oil, Fossil oil, coal	220	Heating Plant	Väst.	Fossil Oil	23
CHP	Väst.	Biomass-based fuel, Coal, Peat, Fuel oil, burnable wastes	220	Integrated bioethanol prod.	Väst.	Cereal straw	90
Heating Plant	Väst.	Fossil oil	70	Integrated bioethanol prod.	Väst.	Cereal straw, wood	90
Heating Plant	Väst.	Fossil oil	12	Integrated bioethanol prod.	Väst.	Cereal straw	90
Heating Plant	Väst.	Fossil oil	5.5	Integrated bioethanol prod.	Väst.	Cereal straw, wood	90
Heating Plant	Väst.	Fossil oil	5.5	Integrated bioethanol prod.	Väst.	Cereal straw	90
Heating Plant	Väst.	Tall oil	5.5	Heating Plant	Söder.[2]	Fossil oil	30
Heating Plant	Väst.	Wood Chips	5.8	Heating Plant	Söder.	Fossil oil	65
Heating Plant	Väst.	Fossil oil	5.5	Heating Plant	Söder.	Fossil oil	65
Heating Plant	Väst.	Wood Pellet	4.5	Heating Plant	Söder.	Fossil oil	65

Type of the plant	Plant location	Fuel type	Installed Capacity (MW)	Type of the plant	Plant location	Fuel type	Installed Capacity (MW)
Heating Plant	Väst.	Biomass-based fuel, peat	5.5	Heating Plant	Söder.	Wood chips	55
Heating Plant	Väst.	Biomass-based fuel, peat	5	CHP	Söder.	Wood chips	110
Heating Plant	Väst.	Fossil oil	5	Heating Plant	Söder.	Bio-oil	5.5
Heating Plant	Väst.	Fossil oil	6.3	Heating Plant	Söder.	Bio-oil	5.5
Heating Plant	Väst.	Fossil oil	9.9	Heating Plant	Söder.	Fossil oil	5.5
Heating Plant	Väst.	Fossil oil	16.5	CHP	Söder.	Recycled Wood	36
Heating Plant	Väst.	Fossil oil	16.5	Heating Plant	Söder.	Wood chips	4
Heating Plant	Väst.	Fossil oil	16.5	Heating Plant	Söder.	Wood Pellet	5.5
Heating Plant	Väst.	Fossil oil	70	Heating Plant	Söder.	Wood pellet	5.5
Heating Plant	Väst.	Fossil oil	70	Heating Plant	Söder.	Bio-oil	2.3
CHP	Väst.	Biomass-based fuel, Wood chips, Pellet, biogas, Electricity	105	Heating Plant	Söder.	Fossil oil	2.9
Heating Plant	Väst.	Wood	6	Heating Plant	Söder.	Fossil oil	10
Heating Plant	Väst.	Wood	15.5	Heating Plant	Söder.	Fossil oil	10
Heating Plant	Väst.	Bio-oil	15	CHP	Söder.	Recycled Wood	100
Heating Plant	Väst.	Bio-oil	12	Heating Plant	Söder.	Recycled Wood	25
Heating Plant	Väst.	Bio-oil	9	Heating Plant	Söder.	Recycled Wood	25
Heating Plant	Väst.	Wood Pellet	4	CHP	Söder.	Wood, bio-oil	25
Heating Plant	Väst.	Wood Pellet	4	Heating Plant	Söder.	Wood, bio-oil	80
Heating Plant	Väst.	Wood Pellet	15				

[1] Västmanland, [2] Södermanland.

OPTIMIZATION OF A REGIONAL ENERGY SYSTEM

Här har en modell för systemoptimering utvecklats som tar hänsyn till att förnybara energikällor införs i systemet. Modellen kan simulera och optimera produktionsplanering med tidsupplösningen per dag och har använts för olika scenarier i Västmanland and Södermanland.

Hela kedjan finns med i modellen och fall med integration av bioetanol har undersökts. Elproduktion från befintlig vattenkraft och vindkraft samt möjlig solelsproduktion från installation av solceller på byggnader har inkluderats i modellen. Såväl bränsleanvändning som beräkning av koldioxidutsläpp finns också med.

En av slutsatserna från projektet är att integrera bioetanolproduktion i ett kraftvärmeverk kan öka den totala tillförseln av värme och el till systemet och minska behovet av elimport.

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