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Rural Residential District Heating in North China

Minor Field Study
MSc Dissertation

Report no. 28

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Lund,
June 2000

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(Fjärrvärme för bostäder på landsbygden i norra Kina)

Sammandrag/ Abstract

Jilin Province in northern China supports the development of thermal gasification applications using agricultural residue as raw material. A demonstration project was launched in spring 2000 to establish a gasification plant in a rural village in eastern Jilin. The ambition is to refine biomass into three new energy carriers: gas, electricity and heat (hot water). The concept is called trigeneration.

This report is the result of a preliminary investigation of rural residential district heating as a strategy for utilising trigenerated heat. Three issues are addressed: (i) estimating demand and usage of heat in rural Jilin households as a basis for heat load predictions, (ii) technical dimensioning of a distribution grid for district heating, and (iii) economy.

Two mathematical models are used to calculate the heat demand of a single household, assumed to be representative of the village of the demonstration project. The results are compared with each other, and with several other estimates of heat usage of households. Technical dimensioning of a distribution grid is performed on the basis of the modelled demand. A rudimentary economic assessment is made with cost estimates based on information from local and foreign sources.

The study suggests that the heat demand of rural households in northern China may be higher than generally assumed according to conventional wisdom. Economic externalities as well as the social context have to be included in a presentation that seeks to motivate the establishment of rural residential district heating based on trigeneration in north China.

Nyckelord/ Key words

Bioenergy, China, cogeneration, district heating, rural residential heat demand
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Joakim Nordqvist
Lund, June 2000

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Preface

This study has been carried out within the framework of the Minor Field Study (MFS) Scholarship Programme, which is funded by the Swedish International Development Co-operation Agency, Sida.

The MFS Scholarship Programme offers Swedish university students an opportunity to carry out two months' field work in a Third World country resulting in a Master's dissertation or a similar in-depth study. These studies are primarily conducted within subject areas that are important for development, and in a country supported by the Swedish programme for international development assistance.

The main purpose of the MFS Programme is to increase interest in developing countries and to enhance Swedish university students' knowledge and understanding of these countries and their problems. An MFS should provide the student with initial experience of conditions in such a country. A further purpose is to widen the Swedish personnel resources for recruitment into international co-operation.

The Centre for International Environmental Studies, CIES, at the Royal Institute of Technology, KTH, Stockholm, administers the MFS Programme for all faculties of engineering and natural sciences in Sweden.

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Summary

In Jilin Province in northern China the political leadership has taken the initiative to promote the development and rural applications of technology for thermal gasification of biomass. Local supply of raw material is plentiful since agriculture, which is an important industry in Jilin, generates an abundance of residue suited for this purpose. The province has a distinct inland climate with hot summers and cold winters.

Two gasification projects have been implemented during 1997 and 1998, and a third one was launched in the spring of 2000. Current plans are to establish a plant in the village of Hechengli, where production of gas will be complemented with additional energy conversion technology. The intention is to equip the new plant with facilities to use the gas for local generation of electricity. The reason is an ambition to increase the plant's output potential, and thereby its profitability. The two existing plants so far only market gas for household use. In the process of electricity generation, excess heat is produced in the form of hot water. This energy might be sold to local customers in demand of heat. Therefore, in Hechengli, the aim is to establish an enterprise that can offer the sale of three different carriers of refined bioenergy: gas, electricity and heat.

This report outlines the prerequisites for using heat from the Hechengli plant for district heating of local residential buildings. Its objective is to constitute a basis for the project management in their decision on how to utilise cogenerated heat. Three issues are addressed. First, the heat demand of local residential buildings is investigated. The results form a foundation for an estimate of the heat load that characterises the village. Second is the issue of technical dimensioning of a district-heating grid in Hechengli and the different technical choices inherent in such a system. Finally, an economic evaluation of the district-heating concept is sketched.

In order to estimate the total *heat load* of Hechengli's residential buildings, this study takes a foothold in one single household, which is considered to be representative of the whole village. Using two different mathematical models based on thermodynamical relations, the *heat demand* per household can be calculated. The results are then compared with three estimates of the actual *heat usage* of rural households in Jilin. The total heat demand of the village, it is assumed, corresponds to the number of households multiplied by the estimated demand per household. Referring to Scandinavian experience of similar cases, distribution loss in the local grid is estimated, thereby enabling an evaluation of the magnitude of the total load.

Residential buildings in rural north China are almost exclusively small, one-storey single-family houses. The modelled building has a heated floor area of about 56 m^2. The mathematical models yield results that indicate a heat demand of between 16.6 and 18.6 MWh per household and heating season. This corresponds to an average thermal power demand of 4.4 to 4.8 kW per household. Dimensioning thermal power demand is estimated at 8.1 kW. On a per-square-metre basis, these results are fairly high compared to the situation in for example Sweden. This circumstance may be explained by the high average heat-transmission coefficient of the modelled building.

The modelled demand can be put in relation to different estimates of the actual heat usage of rural households in Jilin. In this report, the definition of usage includes the effects of energy conversion, as well as the behaviour and habits of residents. Demand does not change with any of these parameters. Three estimates of usage are presented, giving quite diverse results. According to conventional wisdom among local expertise in Jilin, annual heat usage per rural household ought to be about 5 to 8 MWh. Rough calculations based on official Chinese statistics imply average figures of 13 to 15 MWh, while a study of energy flows in an actual household in He-

chengli yields an approximate result of 17 MWh. These three estimates are all lower than the heat usage deduced from the modelled demand.

The overestimation of the modelled results can be explained in part as a consequence of several basic assumptions giving a simplified picture that does not fully concur with actual conditions. For example, the indoor temperature is assumed to be constant at 18 °C in the entire building, twenty-four hours a day, and the contribution of the outer roof to the climate shield of the house is disregarded. Nevertheless, the results are considered to be reasonably accurate in magnitude, although they may not be in conformity with the present, actual heat usage of households in Hechengli. The deviation in relation to the example of the calculated energy flows is sufficiently low in order not to be surprising. The estimates based on conventional wisdom, however, are extremely low. Assumedly, they cannot be applied to the situation in Hechengli, where the standard of living is comparatively high.

In order to picture the heat load of a possible district-heating grid in Hechengli, the modelled results are used as a starting point, even though they are believed to overestimate the current heat demand. Modelling is the only method, which estimates the thermal power demand, required for the construction of so-called duration curves that illustrate the heat load. The load is calculated for the 224 households of the entire village and adjusted with regard to distribution losses equivalent to 10 to 30 %. The result is an average load of between 1.1 and 1.6 MW, and the dimensioning load is estimated to vary around 2.0 to 2.6 MW.

The present situation of technology for district heating in China is dominated by direct systems without combined hot tap-water supply. By *direct* is understood that the same physical medium flows through all three functional parts of the system: the supply circuit, the distribution grid and the end-user circuits. The alternative is an *indirect* system, where heat exchangers at the interfaces separate the media of the different parts. Indirect systems are more complex both technically and operatively, whereas direct systems are less intricate and less expensive, which are thought to be prioritised qualities in the current context. Hot tap-water supply is not considered in this report, since a prediction of how such installations would affect the demand for heat requires closer investigations that reach beyond the framework of this study. Grid temperature levels are assigned values of 80 and 60 °C, respectively. Based on the information above, and a grid structure proposed in the report, pipe dimensions needed to cover dimensioning load are calculated. A strategy of phased expansion of the grid is presumed, with three alternatives of first-phase coverage presented: 84, 112, and 224 households, respectively. Technical aspects of supply stability are addressed in terms of auxiliary and peak-load capacity as well as heat accumulation.

The economic evaluation consists of a rudimentary, quantitative calculation of investment costs, complemented by qualitative discussions about important externalities. Only the following costs are included in the calculation: the purchase of distribution pipes and, when relevant, the purchase and installation of radiator circuits in the homes of the customers and a central heat accumulator. Three grids are presented: 84 households excluding central heat accumulation, and 112 and 224 households, both including accumulators. The investment costs for these grids amount to 1.5, 3.5 and 4.7 million CNY, respectively. Distributed over an economic lifetime of twenty years at an interest rate of four per cent, these figures correspond to annual costs of 1400, 2300 and 1500 CNY per household. As a comparison, the current yearly cost of coal used to heat a household in Hechengli is estimated to be 750 CNY. The economic externalities that are considered in this report refer to both local and global environmental impacts, and to health issues. Factors such as socio-cultural context and policy climate are also given some attention.

The main conclusions of this report may be summarised as follows. First, the heat demand of residential buildings in rural Jilin villages such as Hechengli is probably considerably greater than is commonly assumed according to conventional wisdom. Furthermore, factors such as environmental damage and the level of comfort for residents have to be included in an economic evaluation of district heating in order to motivate the otherwise higher cost in relation to the current system of heating.

综述

在中国东北的吉林省，当地政府正在采取一项推动生物物质热气化技术在农村地区的开发和应用的政策。本地原材料供应是充足的，因为作为吉林省重要产业之一的农业可产生大量可用于此用途的残余物。吉林省的气候属内陆气候，夏季较为炎热，而冬季较为寒冷。

自1997年和1998年以来已经实施了两个气化项目。第三个气化项目将于2000年春季启动。按照目前的计划，将在合成利村建造一座工厂，并将在额外的能量转换技术基础上生产燃料气体。该项目的目的是在新建工厂中配备能利用气体为本地发电的设施。实施此项目的原因之一就是希望提高该工厂的产量和效率。目前的两座工厂只是生产家用的气体。在发电的过程中，多余的热量以热水的形式排出。而热水作为一种能源则可销售给需要取暖的本地客户。所以，合成利项目的目的就是建立一个企业，并销售三种不同形式的精炼生物能源：气体、电力和热能。

本报告将简要介绍使用合成利工厂所排出的热量为本地居民住宅提供暖气的必要条件。本报告的目的是为项目经理人员提供在如何利用废热发电工厂所排出的余热方面进行决策的依据。本报告主要阐述三个问题。首先对本地居民住宅的热能需求进行了调查，根据调查的结果估算了合成利村热能的负载。其次，探讨了在合成利村建立一个区域供暖网的技术规模，以及在这样一个系统中可供选择的不同技术。最后，对区域供暖设计概念进行了经济评估。

为了对合成利村居民住宅的热负荷总量进行估算，本人以该村中十分具有代表性的一家住户为例进行了此次调查。利用两种不同的、以热动力学关系为基础的数学模型对每户的热需求量进行了计算。随后，将计算结果与吉林省农村地区居民住宅的实际热能使用量的三项估算值进行了对比。根据本报告的假设，合成利村热需求总量应该等于居民住户数量乘以每户估算需求量。另外还根据北欧地区类似情况的数据对本地供热网络的配热损失进行了估算，并进而对总体热负载的规模进行了评估。

中国东北农村地区的民宅几乎毫无例外地都是单层独户小型住宅。模型中所使用的居民住宅取暖面积约为56平方米。数学模型所得出的结果表明，每户每个取暖季节的热需求量约为16.6到18.6兆瓦时。这就相当于每户住宅平均热需求量在4.4到4.8千瓦之间。热需求量的规模估计为8.1千瓦。如果按照平方米计算，则这些结果与瑞典的情况相比还是比较高的。出现这种情况的原因可能是，在模拟居民住宅中平均热传导系数较高。

根据模型所得出的热需求量可以与吉林省农村地区居民住宅的实际热使用量的不同估算数值之间建立一定的关系。在本报告中，确定使用量的要素包括能量转换效应，以及居民的行为和习惯。热需求量不会随这些参数中的任何一个而改变。报告中采用了三种使用量估算方法，并得

出了相当不同的结果。根据吉林省当地专业人员的常识，农村地区居民住宅每户年热能使用量应该在5到8兆瓦时之间。根据中国官方的粗略统计，结果为13到15兆瓦时，而根据对合成利村一户居民住宅所进行的实地能量流动研究的结果，这个数值约为17兆瓦时。但是，根据从模拟热需求量所推导出来的热使用量，这三个估算值都偏低。

模拟研究结果偏高的部分原因应归咎于若干基本假设的结果，根据这些假设所得出的结果并不与实际条件完全相符。例如，本人假设了在整个居民住宅中每天24小时均保持18°C的恒定室温，而且，根本就没有考虑外部屋顶对于气候屏蔽的作用。尽管如此，本人仍然认为估算结果在一定程度上还是比较准确的，当然，此结果可能会与合成利村居民住宅目前实际热使用量不完全相符。因为与所计算的能流范例相关的偏差很小，所以也还算合理。但是，根据常识所估算的结果却太低。以此推断，这样的结果不适用于合成利村的情况，因为该村的生活水平相对较高。

为了能够勾画出合成利村可能的区域供暖网络热负载情况，本报告使用了根据模型所得出的结果作为出发点，尽管这些结果可能过高地估算了当前的热需求量。模拟是唯一可采用的方法来估算热力需求量，并据此勾画出能描述热负载的所谓的持续曲线。本人是根据全村224户居民住宅计算出热负载的，并根据配热损失系数（在10%到30%之间）对其进行了调整。结果是平均热负载在1.1和1.6兆瓦之间，负载规模估计在2.0到2.6兆瓦之间。

中国的区域供暖目前所采用的主要技术仍然是直接供热系统，水龙头没有热水供应。之所以说“直接”这个词，就是表示相同的物理介质流经系统的所有三个功能部分：供热管路、配热网络和最终用户管路。而与此相反的技术就是“间接”系统，即在接口处安装换热器，使介质被分隔在不同部分之间。从技术和操作上看，间接系统更加复杂，而直接系统则更为简单也更为便宜，目前在中国仍是首选的供热技术。本报告中没有考虑水龙头供应热水的问题，因为对于这种设备将会怎样影响热需求量的预测要求对此进行更进一步的研究，这就超出了此项研究的范围。网络中供热介质的温度范围赋值在80到60°C之间。根据上述信息以及本报告中所假设的网络结构，还对能够承受如此规模的热负载的管路尺寸进行了计算。本人认为，最好采用一种分阶段扩建供热网络的策略，并提出了三种可用于第一阶段网络扩建的方式：84户、112户和224户。此报告还从辅助能力、峰值热负载能力、以及热积累等方面探讨了供热稳定性的技术问题。

经济评估过程是由对投资成本进行的初始定量计算构成的，本报告还对重要的外部条件进行了定性探讨。在计算中只考虑了以下成本：购买配热管路的成本，购买并在用户住宅内安装散热器管路的成本，以及购买和安装中央集热器的成本。本报告提出三种供热网络方案：不含中央集热器的84户住宅，包括集热器的112户住宅和224户住宅。这三种供热网络的投资分别为150万、350万和470万元人民币。考虑到二十年的经济寿命周期和每年4%的利率，将这些成本分摊到每年之后就能得出每户居民住宅年成本分别为1400元、2300元和1500元人民币。在此可以进行一项对比，合成利村的每户居民住宅使用煤炭供暖的年成本为750元人民币。此项目所造成的经济效益涉及到对本地和全球环境的影响，以及对健康的影响问题。此报告还适当地考虑了社会文化背景和政府政策气候等问题。

本报告的结论总结如下。首先，诸如合成利等吉林省农村地区村民住宅的热需求量可能比按常识所估算的数值高得多。其次，在对区域供暖系统进行经济评估时必须考虑对环境的破坏以及对居民舒适程度的影响等问题，这样才能促动人们选择相比目前的供暖系统成本更高的区域供暖系统。

Sammanfattning

I provinsen Jilin i norra Kina har den politiska ledningen tagit initiativ för att befordra utveckling och tillämpning av teknik för termisk förgasning av biomassa på landsbygden. Den lokala tillgången på råvara är mycket god eftersom jordbruket, som är en betydelsefull näring i Jilin, genererar rikliga mängder växtrester. Provinsen har ett utpräglat inlandsklimat med varma somrar och kalla vintrar.

Två förgasningsprojekt har genomförts under 1997 och 1998, och ett tredje sjösätts under våren 2000. I byn Hechengli planeras uppförandet av en anläggning där avsikten är att inte bara producera gas, utan att även använda gasen till lokal elproduktion. Anledningen till detta är en ambition att öka anläggningens avsättningspotential och därmed dess lönsamhet. De två befintliga anläggningarna saluför hittills endast hushållsgas. Vid elproduktion genereras överskottsvärme i form av varmvatten, som eventuellt kan säljas till lokala kunder med värmebehov, och i Hechengli ämnar man därför försöka utöka den nya anläggningens produktomfång till tre bärare av förädlad bioenergi: gas, elektricitet och värme.

Den här rapporten beskriver förutsättningarna för att använda värmen från Hechenglianläggningen till fjärrvärme för byns bostäder. Syftet är att utgöra underlag för projektledningen i ett beslut om hur värmen skall avsättas. Tre frågeställningar behandlas. Först utreds värmebehovet i de lokala boningshusen. Resultaten ligger till grund för en uppskattning av den värmelast byn motsvarar. Den andra frågeställningen rör den tekniska dimensioneringen av ett lokalt fjärrvärmenät och de olika ställningstaganden som därvidlag måste göras. Slutligen utförs en översiktlig ekonomisk utvärdering av fjärrvärmekonceptet.

För att uppskatta Hechenglis totala *värmelast* för uppvärmningen av dess bostäder utgår studien från ett hushåll, vilket betraktas såsom representativt för hela byn. Genom att använda två matematiska modeller baserade på termodynamiska samband kan *värmebehovet* per hushåll beräknas. Resultaten jämförs med tre uppskattningar av den faktiska *värmeanvändningen* i hushåll på Jilins landsbygd. Byns sammanlagda värmebehov antas motsvara antalet hushåll multiplicerat med det uppskattade värdet per hushåll. Med hänvisning till skandinavisk erfarenhet av liknande fall ansätts distributionsförlusterna i det lokala fjärrvärmenätet, varefter en bedömning av den totala värmelasten är möjlig.

Bostadsbebyggelsen på den nordkinesiska landsbygden består så gott som uteslutande av små enfamiljshus i ett plan. Den modellerade byggnaden har en bostadsyta på ungefär 56 m^2. De två matematiska modellerna ger resultat som indikerar ett värmebehov på mellan 16,6 och 18,6 MWh per hushåll och säsong, vilket motsvarar ett genomsnittligt effektbehov på 4,4 till 4,8 kW per hushåll. Som dimensionerande effektbehov erhålls uppskattningen 8,1 kW. Räknat per kvadratmeter ger dessa resultat ett tämligen högt värmebehov jämfört med svenska förhållanden. En förklaring är byggnadens höga genomsnittliga värmegenomgångskoefficient.

Det modellerade behovet kan ställas i relation till olika uppskattningar av den faktiska värmeanvändningen i Jilins landsbygdshushåll. Användningen är i denna rapport definierad så att den till skillnad från behovet omfattar energiomvandlingsförluster samt de boendes beteende och

vanor. Tre uppskattningar redovisas, vilka sinsemellan ger mycket skilda resultat. Enligt gängse uppfattning bland lokal expertis i Jilin bör årsanvändningen per hushåll på landsbygden motsvara cirka 5 till 8 MWh. Överslagsräkning baserad på officiell kinesisk statistik däremot, resulterar i siffror på i medeltal 13 till 15 MWh, och en studie av energiflödena i ett faktiskt hushåll i Hechengli ger ett värde på ungefär 17 MWh. Alla tre uppskattningarna är lägre än den värmeanvändning som modellresultaten av värmebehovet motsvarar.

Överskattningen i modelleringen kan delvis förklaras av att flera grundläggande antaganden ger en förenklad bild som inte exakt motsvarar de verkliga förhållandena. Till exempel antas innetemperaturen vara konstant 18 °C i hela byggnaden under dygnets alla timmar, och yttertakets bidrag till klimatskärmen försummas. Icke desto mindre bedöms modellresultaten vara rimliga i storleksordning, även om de förmodligen inte speglar den faktiska värmeanvändningen i Hechengli idag. Avvikelsen gentemot exemplet med de beräknade energiflödena är tillräckligt liten för att inte vara uppseendeväckande. Den gängse uppfattningen om värmeanvändningen på landsbygden i Jilin är däremot mycket låg och kan sannolikt inte tillämpas för att uppskatta situationen i Hechengli, där levnadsstandarden är förhållandevis hög.

För att gestalta värmelasten i ett eventuellt fjärrvärmenät i Hechengli används modellresultaten som utgångsvärde, trots att de tros överskatta dagens värmebehov. Modelleringen är nämligen den enda metod som uppskattar effektbehovet, vilket behövs för att konstruera så kallade varaktighetsdiagram som illustrerar lasten. Lasten beräknas för byns 224 hushåll och justeras med avseende på distributionsförluster, vilka antas motsvara 10 till 30 %. Resultatet blir en genomsnittlig last mellan 1,1 och 1,6 MW, och den dimensionerande lasten hamnar under givna förutsättningar mellan 2,0 och 2,6 MW.

Vad gäller teknikval är den allmänna situationen för fjärrvärme i Kina sådan att direkta system utan tappvarmvattenberedning är de vanligaste. Med *direkt* menas att det är samma medium som leds i nätets alla tre delar: tillförsel-, distributions- och abonnentkretsarna. Alternativet är ett *indirekt* nät, där dessa kretsar är åtskilda genom värmeväxlare. Indirekta nät är därför mer avancerade, både tekniskt och driftmässigt. Direkta nät är enklare och mindre investeringstunga, vilket förutsätts vara prioriterat i detta sammanhang. Beredning av tappvarmvatten lämnas utanför systemet i denna rapport, eftersom en bedömning av hur sådana installationer skulle påverka efterfrågan på värme kräver närmare utredningar, som dock faller utanför den här studiens ramar. Temperaturnivåerna i nätet ansätts till 80 respektive 60 °C. På grundval av det ovanstående och en i rapporten postulerad nätstruktur beräknas rördimensionerna som krävs för att täcka dimensionerande last. Strategisk inriktning för utbyggnaden antas vara en etappvis expansion av nätet, och tre täckningsalternativ för första etappen presenteras: 84, 112 och 224 hushåll. Tekniska aspekter av leveranssäkerhet berörs i form av reserv- och spetslastkapacitet samt värmeackumulering.

Den ekonomiska utvärderingen består av en rudimentär, kvantitativ beräkning av investeringskostnader kompletterad med kvalitativa resonemang om viktiga externaliteter. Medtagna i beräkningen är endast följande kostnader: inköp av distributionsrör samt i förekommande fall inköp och installation av central värmeackumulator och radiatorkrets hos kund. Tre nät redovisas: 84 hushåll exklusive ackumulator, samt 112 och 224 hushåll inklusive ackumulator. Investeringarna för dessa nät uppgår till 1,5; 3,5 respektive 4,7 miljoner CNY. Fördelade över en ekonomisk livslängd på tjugo år till fyra procents ränta motsvarar beloppen 1400, 2300 och 1500 CNY per hushåll och år. Som jämförelse kan nämnas att den nuvarande årliga kostnaden för inköp av kol till uppvärmning av ett hushåll i Hechengli uppskattas till 750 CNY. Ekonomiska externaliteter som behandlas rör lokal och global miljöpåverkan såväl som hälsoförhållanden, och kontextuella faktorer såsom sociokulturellt sammanhang och lokalt policyklimat lyfts fram.

Slutsatserna av rapporten är sammanfattningsvis följande. För det första är värmebehovet för bostadsuppvärmning i byar såsom Hechengli på Jilins landsbygd sannolikt betydligt större än vad som enligt gängse uppfattning förmodas gälla. Vidare måste andra faktorer såsom miljöförstöring och ökad bekvämlighet för de boende inkluderas i en ekonomisk bedömning för att motivera den annars högre kostnaden för fjärrvärme relativt nuvarande uppvärmningssystem.

Figure 1. Map of north-eastern China

1. Introduction

1.1 Background

Jilin is a province in north-eastern China, about 187 000 km^2 in size (Cao *et al*, 1997) and with a population (in 1997) of just under 27 million (CSY, 1998). The number or rural residents in 1996 amounted to 15 million (CREY, 1997). Jilin borders the Heilongjiang Province in the north, Inner Mongolia Autonomous Region in the west, Liaoning Province in the south-west, and North Korea and Russia in the south-east. The provincial capital, Changchun, is located in the centre of the province, approximately 900 km to the north-east of Beijing, and 550 km to the west of Vladivostok. The province has a distinct inland climate with warm summers, average 25 °C in July, and cold winters, average –16 °C in January (CSY, 1998).

Agriculture is an important economic sector in Jilin, and the province is one of the leading producers of maize in China. The annual output of maize amounts to more than 17.5 million tonnes. Other major crops are rice and soybeans. Straw and stalk from agriculture constitutes an abundant resource with promising development potential for commercial utilisation, which has been recognised by the provincial authorities (Cao *et al*, 1997; Liu, 1999). Also, the Jilin Province leadership is strongly committed to the local development of a modern and sustainable rural energy industry, based on agricultural biomass as raw material. To promote this development the provincial government has set up a special leadership group[*] which, among other things, works to foster international co-operation (Liu, 1999).

1.1.1 Hechengli biomass gasification project

Following the successful implementation of two previous biomass gasification projects in Shijiapu (south-central Jilin, 1997) (JPERI, 1998) and Baicheng (western Jilin, 1998) (Mao, 1999), the provincial Environmental Protection Agency is now (spring 2000) launching a new demonstration project for thermal gasification using agricultural residue as raw material. The site chosen is the village of Hechengli in eastern Jilin. The project, which has been conceived through close co-operation between Jilin's leadership group and the Working Group for Energy Strategy and Technology of the CCICED, is the first within the framework of the local commitment to rural bioenergy to be implemented in a context of deep involvement of international partners. Funding for the project is supplied by the UNF and administered by the UNDP. International contributions in the areas of science and technology include efforts at Princeton University, USA, while Jilin environmental authorities contribute local expertise and experience.

The project in Hechengli differs from its two predecessors in Jilin in one significant way. Whereas the plants in Shijiapu and Baicheng only produce gas for household use, it is the objective of the project management for Hechengli that the new plant will be used for so-called *trigeneration*. The meaning of this concept is that the input of agricultural residue will be refined into three different energy carriers: gas, electricity and heat (hot water), which can be sold as separate products. The reason for wanting to expand the product range is twofold. First, by using gas not only for sales to domestic customers but also for electric generation on site, there is room to increase the gas production capacity, which in turn may help to increase profitability. Second, electric generation, whether in gas turbines or internal combustion engines, also generates considerable amounts of heat. By selling this heat as a product instead of discarding it as waste,

[*] Jilin Province Rural Biomass Energy Development Leadership Group, chaired by provincial Vice-Governor Madame Liu Shuying.

the energy content of the raw material can be efficiently utilised, without unnecessary waste of resources.

The reasons for choosing Hechengli as the site of the third biomass gasification plant in Jilin were many, and the location was selected in competition with several other candidate villages. The following factors were all considered favourable to Hechengli in the final decision. Most importantly, perhaps, the living standard of Hechengli is relatively high in comparison with rural Jilin in general. An average income in Hechengli is estimated to be 5000 CNY per person per year, and this may be an indication of a high energy demand as well. Furthermore, Hechengli, being labelled the "First Ecological Village of China", has already made itself known as a place where environmental concerns are a priority, and where an awareness of environment-related issues is spreading. Some importance was also attributed to the fact that from a comprehensive planning perspective, Hechengli's location in the eastern part of the province gives the three present projects of the biomass initiative a desirable geographical distribution (Yin, 1999-11-03; Li, 1999-11-08).

1.1.2 Description of Hechengli

Hechengli is a rural village in Longjing County on the border with North Korea (see Figure 1 on the previous spread). It is located in Yanbian Prefecture, an autonomous region in eastern Jilin, where 70 % of the population are ethnic Koreans. The village itself is situated on the southern perimeter of Longjing town, which has an urban population of about 90 000. The whole county, with 280 000 residents, covers 2600 km^2. The most important crops are maize, rice and beans with annual outputs of 40 000, 19 000, and 13 000 tonnes, respectively.

Hechengli consists of 224 households and some 670 inhabitants, of which 5 % are Korean. Immediately south of Hechengli lies Xinhuatun, a sister village, totally Korean and comprising 85 households. All residents of Hechengli own land in the surroundings, and agriculture is the dominating means of livelihood. The landscape is hilly, and vegetables are the main type of crop. Wooden structures that can be covered with transparent plastic to function as greenhouses are commonplace. Other local industries are fishing and fish breeding, for which there are several ponds along the nearby Liudao River. In the centre of the village there is a poultry-raising plant producing broiler chickens and eggs, and adjacent to this facility there is a plant for the production of soil fertiliser from chicken manure. Because of environmental restrictions, industries that pollute air or water are not allowed to establish themselves in this area, which is located between two important drinking-water catchments. Also, the predominant wind direction would drive any air pollutants from Hechengli right into urban Longjing. Because of the environmental awareness expressed in local regulations, Hechengli and Xinhuatun together have been appointed the "First Ecological Village of China."

The standard of living in Hechengli is relatively high compared with rural conditions in general. Annual incomes range between 2000 and 8000 CNY per person[*]. All households have electricity and running cold tap-water. 80 % are connected to the communal sewage system, and modern commodities such as telephones, radio and television sets, fridges and freezers, and washing machines are generally found in well-to-do families. For cooking and heating, 60 % of Hechengli's households use coal, and the remainder use firewood. Stalk and other agricultural residues, which are common fuels in other parts of rural Jilin, are not used very much in Hechengli, since vegetables rather than stalk-growing crops are grown in this particular area. The fuel is burned in the kitchen stove, and the heat is dispersed through the kang, a low brick

[*] In comparison, all-China average annual per capita disposable income of urban residents in 1997 amounted to 5160 CNY. The corresponding figure for the net income of rural residents was 2090 CNY (CSY, 1998).

platform, through which the hot smoke and fumes from combustion are led on their way to the chimney. The kang, normally located in a room adjacent to the kitchen, is not only a heating device. It is also used to sit on for work or leisure, and with mattresses rolled out on top it becomes a bed. Kangs and other internal flue structures are used for household heating all over northern China, but in Hechengli many households have installed hot-water radiators as a complement to traditional heating technology.

1.2 Objectives

The main objective of this study was to provide sufficient input to enable the management of the bioenergy project at Hechengli to make a strategic decision in the initial phases of the project. The question at hand is whether or not to further consider local district heating* as a practical option for the intended utilisation of excess heat from electricity generation at the demonstration plant. Therefore, the primary objectives of this study were:

1. to establish a credible estimate of the heat demand of an average household in Hechengli in order to clarify the conditions for a match between the supply of heat from the plant and the actual need for local residential space heating.
2. to record the basic technical conditions for an operable district-heating system in Hechengli, and to illustrate some of the different options for the choice of district-heating technology.
3. to make a rough prediction of the economic implications of the district-heating option based on these observations.

A secondary objective of the study was to lay the foundation for possible further investigations and engineering, required if the project management should decide to pursue a course of action for Hechengli that includes district heating.

It was not the purpose of this report to advise the management on how to act, but simply to point out important implications of a decision to develop district heating in Hechengli. The final decision involves weighing political, economic and financial priorities, which will be left for the parties responsible for the project to settle.

1.3 Methodology

1.3.1 Heat demand, usage and load

By determining the heat demand of one household, considered to be typical for Hechengli, it is possible to estimate the heat demand of the entire community. This demand will reflect the load that has to be borne by a local district-heating grid. There are two dimensions of the heat demand which both have to be identified. These are the dimensioning thermal power demand and the annual thermal energy demand.

To obtain an estimate of the thermal power demand of a household, a mathematical model is used, which is based on the physical properties of a building and its climate shield (Frederiksen and Werner, 1993). These are the fixed parameters, whereas outdoor temperatures are variable input. By feeding local extreme-temperature data into the model, it is possible to predict the dimensioning thermal power demand of the household and the community. Using temperature data for the whole heating season enables the estimation of the thermal energy demand, as well as

* In this report the term *district heating* is to be understood as a technical system of pipes and other equipment, which, using water as a medium, transfers heat from a central heat source to residential buildings only, for the purpose of wintertime space heating and possibly for water heating.

the fitting of a duration curve of the theoretical heat load of a prospective district-heating grid. The actual heat load, which is also dependent on the choice and performance of technology, is only commented upon.

In order to achieve a higher degree of significance, the results given by the temperature-input model are compared with the output from another mathematical model based on a relation used in China to determine the thermal energy demand of urban residential buildings (Lang and Huang, 1993). This relation uses the degree-day concept to account for seasonal variations in temperature, and does not allow conclusions to be drawn about the magnitude of dimensioning thermal power demand.

The results from both models are compared with estimates of the actual annual energy usage of a real household. The estimates are based mainly on information acquired in interviews and on published statistical data.

1.3.2 District-heating technology

Based on literature about district-heating technology, on interviews with local and foreign experts or laymen and observations made on site in Hechengli, a brief survey of the conditions for local district heating has been made. The purpose is to convey a basic understanding of important aspects of applied district heating, and its significance and possible consequences in Hechengli. Designation of quantitative data is used to concretise some examples and results. Although there is an ambition to make all data representative for local conditions and credible in the given context, they have to be considered as estimates only, awaiting the results of possible detailed project investigations in the future. Similarly, recommendations or implicit choices with regard to technology are made as illustrative cases, which are meant to be further evaluated before final decisions about detailed solutions are made.

1.3.3 Economic implications

The study includes a rudimentary economic assessment of the installation of district-heating equipment selected under the premises stated above. The economic implications of a district-heating grid in Hechengli include not only the financial aspects of investment costs, however, and it is the ambition of this report to exemplify this. By drawing information from the literature, and from opinions and experience of locals as expressed in interviews, other topics of economic relevance are presented in a qualitative discussion. No explicit calculations or other quantitative evaluations are attempted. Although of great interest, such exercises fall outside the scope of the present report.

2. Heat demand, usage and load

2.1 Modelling the heat demand of a building

The two mathematical models used in this report to estimate the heat demand of a building are alike in the sense that they both require indoor temperatures and mathematically represented data, describing physical characteristics of ventilation and the climate shield (or envelope) of the modelled building, as fundamental input. These properties are regarded as fixed unless manipulated for the purpose of investigating the robustness of the models. The actual numerical values used in this study are introduced and discussed in a later section of the report.

The first model is based on the outdoor temperature (T) as variable input, yielding the thermal power demand (P) as primary output. The second model, on the other hand, directly estimates the thermal energy demand (Q) as a function of degree-day numbers (D). Therefore, in this report, the models will be referred to as the P(T) model and the Q(D) model, respectively. The degree-day concept is a conventional method in space-heating engineering used to represent site-specific temperature data that are statistically averaged over long periods of time (Frederiksen and Werner, 1993).

2.1.1 Thermal power demand – the P(T) model

Applying the P(T) model, it is possible to estimate the thermal power demand of a building as a function of variable outdoor temperatures. This allows for the construction of theoretical duration-curve diagrams over a heating season, as well as predictions of average and dimensioning power demands. Having established satisfactory and representative mathematical values for the different fixed and variable parameters, using the model simply means solving the following equation (Frederiksen and Werner, 1993):

$$P=(\sum kA+(1-\eta)\cdot n\rho cV)\cdot(T_i-T) \qquad (1)$$

P = thermal power	[W]
k = heat-transmission coefficient of envelope element	[W/m^2K]
A = area of envelope element	[m^2]
n = air exchange rate	[h^{-1}]
ρ = density (of air)	[kg/m^3]
c = heat capacity (of air)	[Wh/kgK]
V = enclosed air volume	[m^3]
η = efficiency coefficient of heat exchanger for heat recovery	[—]
T_i = desired indoor temperature	[°C]
T = prevailing outdoor temperature	[°C]

In shorthand notation, the equation can be reduced to: $P=(\Pi_{trans}+\Pi_{vent})\cdot\Delta T$ (1a)

Π_{trans} = specific thermal power demand due to transmission = $\sum kA$	[W/K]
Π_{vent} = specific thermal power demand due to ventilation = $(1-\eta)\cdot n\rho cV$	[W/K]
ΔT = temperature difference = T_i-T	[K]

The summation, $\sum kA$, indicates the addition of components of specific thermal power demand due to heat transmission through the different elements of the envelope of the building, such as walls, floor, roof, *etc.* For each such element, according to Swedish authority regulations, the following relation applies (Boverket, 1993):

$$k=\alpha_1\alpha_2\{(R^{-1}+\delta k)-\alpha_{sol}\} \qquad (2)$$

α_1 = correction factor for heat storage (in the ground)	[—]
α_2 = correction factor for standard indoor temperature	[—]
R = thermal resistance	[m^2K/W]
δk = correction term for model imperfections	[W/m^2K]
α_{sol} = solar correction term	[W/m^2K]

In the following, and in order to facilitate calculations, the correction factor for standard indoor temperature (α_2) and the correction term for model imperfections (δk) are disregarded. Omitting α_2, however, which for standard conditions equals one, ought not to influence the calculation much. Disregarding δk, which is greater than or equal to zero, leads to a marginal underestimation of the heat-transmission coefficient. This, in turn, means that the final estimate of the thermal power demand might possibly be a little too low. As will be seen further on in this report, however, low results are not a problem when applying the model in this particular case. Finally, the expression above as is rewritten as:

$$k=\alpha_1(R^{-1}-\alpha_{sol}) \qquad (2a)$$

As defined in Swedish regulations, the solar correction term (α_{sol}) applies only to windows. It accounts for passive solar heating and varies depending on which direction the windows face. Similarly, the reduction factor due to heat storage (α_1) only applies to parts of the envelope not exposed to outside air. The thermal resistance (R) is determined by the following relation (SIS, 1989):

$$R=R_i+\sum R_j+R_e \qquad (3)$$

R_i = internal heat transfer resistance to air	[m^2K/W]
R_j = thermal resistance of a plane layer "j"	[m^2K/W]
R_e = external heat transfer resistance to air	[m^2K/W]

where, for homogenous plane material layers (SIS, 1989), $R_j=đ_j/\lambda_j$ (4)

đ = thickness	[m]
λ = heat conductivity coefficient	[W/m,K]

For soil types and unventilated plane layers of air, there are tabulated values for R_j.

2.1.2 Thermal energy demand – the P(T) model

The P(T) model can also be used to estimate the thermal energy demand for space heating of a building. With access to data describing local variations in temperature with time, T=T(t), it is possible to sketch a profile of the thermal power demand during a specified period. The thermal energy demand is represented by the integral of power over time, $Q=\int P(T)dt$. For convenience, however, the following equation is used to calculate the magnitude of this integral over a heating season:

$$Q_{hs}=P(T_{ave})\cdot 24Z \tag{5}$$

Q_{hs} = thermal energy demand of a heating season [Wh]
T_{ave} = average outdoor temperature during a heating season [°C]
Z = duration of a heating season [days]
24 is a unit conversion factor [h/day]

2.1.3 Thermal energy demand – the Q(D) model

The Q(D) model is an alternative method for direct calculations of the thermal energy demand of a building, often used in district-heating applications (Frederiksen and Werner, 1993). It is illustrated by the following relation:

$$Q_{hs}=Q_{trans}+Q_{vent}-Q_{ih} \tag{6}$$

Q_{trans} = heat loss due to transmission [Wh]
Q_{vent} = heat loss due to ventilation and infiltration of air [Wh]
Q_{ih} = heat gain by internal heat (from people, cooking, appliances, *etc.*) [Wh]

Here, according to the Standard for Energy Conservation Design of Civil Buildings, which was approved by the Chinese Ministry of Construction in 1986, and which applies to urban residential buildings in China, the terms should be calculated as follows (Lang and Huang, 1993):

$$Q_{trans}=\sum \varepsilon kA\cdot 24\{D_{hs}+Z(T_{ai}-T_{b})\} \tag{7}$$

$$Q_{vent}=n\rho cV_{inf}\cdot 24\{D_{hs}+Z(T_{ai}-T_{b})\} \tag{8}$$

$$Q_{ih}=q_{ih}A_{o}\cdot 24Z \tag{9}$$

ε = solar correction coefficient for an envelope element [—]
D_{hs} = degree-day number per heating season [K·days]
T_{ai} = average indoor temperature [°C]
T_b = base temperature used for calculating degree-days [°C]
V_{inf} = infiltration rate [m^3]
q_{ih} = specific internal heat gain [W/m^2]
A_o = floor area of building [m^2]

In these expressions, solar correction coefficients (ε) are defined as not being unity for all parts of the building envelope exposed to solar light (*i.e.* not only for windows). Of course, they also vary with the points of the compass and, like degree-day numbers, they are unique to any specified geographical location. Since the Q(D) model uses an alternative method to account for solar heat gain, compared to the P(T) model, the expression used when calculating heat-transmission coefficients (k) (*i.e.* Equation 2a) must be modified accordingly, omitting solar correction terms (α_{sol}):

$$k=\alpha_1 R^{-1} \tag{10}$$

The other parameters referred to above are constants.

2.1.4 Thermal power demand – the Q(D) model

Since the degree-day number, used as input for the Q(D) model, already contains averaged temperature data, it is not possible to use this model to estimate the dimensioning thermal power demand. However, the average thermal power demand can be calculated as:

$$P=Q_{hs}/24Z \qquad (11)$$

2.1.5 Differences between the P(T) and Q(D) models

Such as they are described above, the P(T) and Q(D) models differ in that the latter accounts for internal heat gain, whereas the former does not. Also, they use different methods for solar correction. To improve the comparability between the two models in this report, these differences are addressed as follows.

Internal heat gain is normally incorporated into the P(T) model by substituting the desired indoor temperature (T_i) of Equation 1 by the so-called effective indoor temperature (T_{ei}) (Frederiksen and Werner, 1993):

$$T_{ei}=T_i-q_{ih}A_o\cdot(\Pi_{trans}+\Pi_{vent})^{-1} \qquad (12)$$

Note that the effective indoor temperature is not the same as the average indoor temperature (T_{ai}) as specified in the Q(D) model, and that they should not be confused with each other.

Of the two methods described for solar correction of heat-transmission coefficients (k), one uses correction terms (α_{sol}), and the other uses correction coefficients (ε). Henceforth, they will be referred to as the α method and the ε method, respectively.

The ε method is the more complex in that modifications to k values are made for all parts of the building envelope (except for the floor), and that separate sets of coefficient values are specified for different geographical locations (cities) within China (Lang and Huang, 1993). Though studying a household in Hechengli, ε values for Changchun are used, since in this respect the two locations are treated as being equivalent.

As described in the regulations of the Swedish Board of Housing, Building and Planning, the α method modifies k values for windows only, and the set of values that is recommended applies to the whole country (Boverket, 1993). This corresponds to a geographical location between the latitudes of 55° and 70°. In this report, these α_{sol} values are applied to Hechengli as well, even though the village is located at approximately 43° N. Consequently, the α method may somewhat underestimate the need for solar correction at Hechengli, since the amount of sunlight during the heating season is greater there than in Sweden. However, as the α correction only applies to a very small percentage of the total envelope area, this error is assumed to be negligible.

To make transparent the effects of the different methods for solar correction, calculations that both include and exclude solar correction terms or coefficients will be presented. Excluding, of course, means setting α_{sol} equal to zero or ε equal to one for all parts of the envelope. However, since the models and solar correction methods are retrieved from different sources, the α method is used only for compensating the P(T) model, and the ε method for the Q(D) model, to avoid combining possibly disparate models and methods.

Another important point to be noted is the apparent discrepancy in effect that the number of days of the heating season (Z) exhibits when using the different models as methods to calculate energy demand (Q_{hs}). Whereas in the P(T) model an increase in Z, in accordance with natural intuition, leads to an increase in Q_{hs}, the opposite may seem to be the case in the Q(D) model (refer to Equations 7 and 8). Such, of course, is not really the case, and the reason for the seeming contradiction is simply this. In reality, the degree-day number per heating season (D_{hs}) varies with Z, but in this study the explicit connection between the two is not known. Therefore, D_{hs} is simply assumed to be constant. The consequence is that since D_{hs} cannot be correctly modified, the input parameter Z should not be altered for the sake of comparing the two models.

2.2 Model input parameters

The P(T) and Q(D) models have been applied to a theoretical building with dimensions and characteristics as shown in Figure 2. The properties of this building are based on actual conditions in the home of Mr Hua Jisheng in Hechengli, as observed during a visit on 8th November 1999, which was organised by Longjing EPA and Mr Li Yuzong, the Director of Hechengli's Village Committee. The house of Mr Hua is assumed to be representative of all residential buildings in the village. The numerical values of heat conductivity, thermal resistance, *etc.*, are taken from sources published elsewhere, as indicated below.

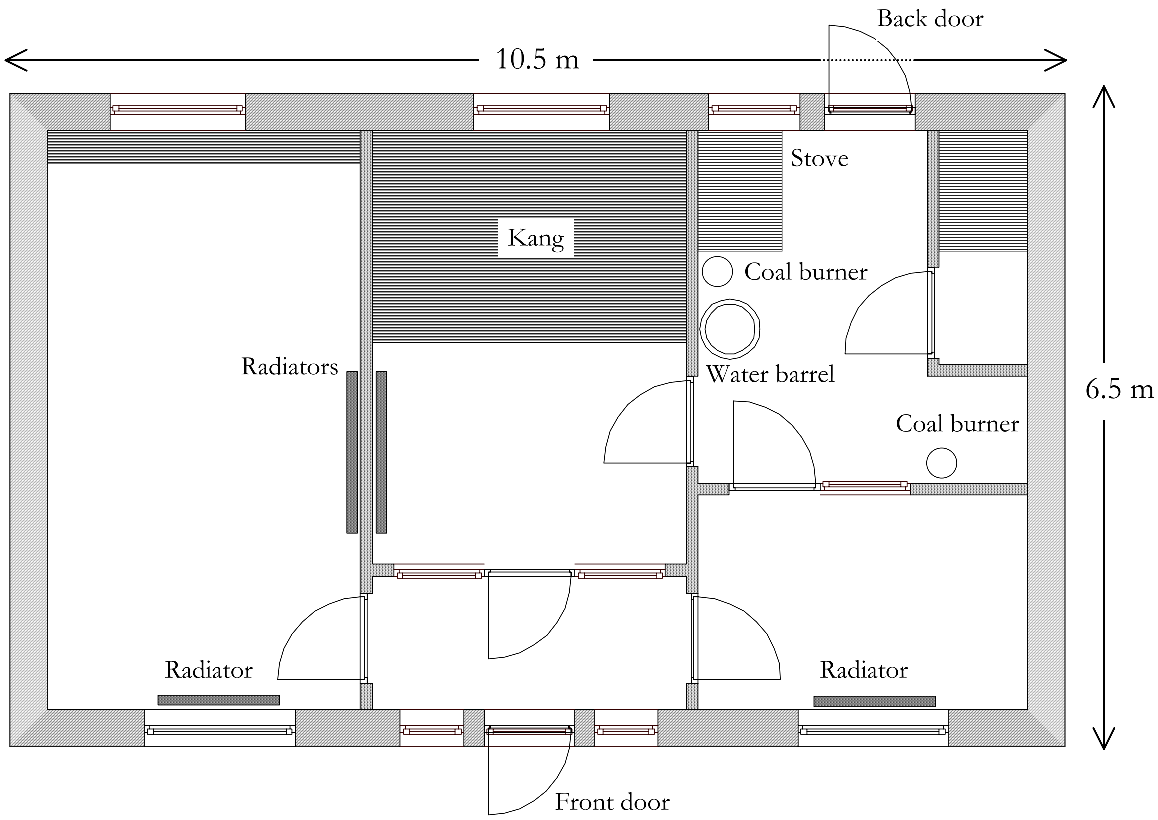

Figure 2. A typical residential building in Hechengli (Hua, 1999-11-08)

2.2.1 Dimensions and materials

The modelled residential building is a single-storey brick house with outer dimensions 10.5×6.5 m^2. The front façade faces south, where there is a square front yard. South of the yard there is a storage building of the same size as the house. The northern façade of the residential building faces a small back yard. The exterior walls are of an uninsulated, three-layer brick construction, 0.37 m thick. (Brick dimensions, including mortar, are typically 60×120×240 mm^3.) This means that the heated floor area (A_o) is about 56 m^2. The distance from floor to ceiling is 2.8 m, and the slanted outer roof is coated with asbestos shingle. (For simplicity, however, this roof is not included in the mathematical modelling, which therefore may somewhat exaggerate calculated demand.) Resting on top of the ceiling is a 0.3 m insulating layer of sawdust. The concrete floor, which is about 25 mm thick, covers a foundation of crushed stone or macadam, 0.5 m deep, on top of a 0.8 m thick layer of sand.

There are two large windows and one door in each of the façades facing south and north, with a smaller window adjacent to the back door. The front door has a small window on each side. These windows all have double glazing, where the glass panes are 0.1 m apart and roughly 3 mm thick. The doors are made of wooden panels, 30 mm thick, with a single glass pane in the upper part of the panel. Above both doors there is another single glass pane. The gables facing east and west have neither doors nor windows. Dimensions are displayed in Table 1.

Table 1. Dimensions of doors and windows of the modelled building (Hua, 1999-11-08)

Object	Orientation		Width [m]	Height [m]	Area [m^2]	Number	Area [m^2]
Doors	North/South	Frame	0.88	2.35	2.1	1	2.1
		Panel pane	0.60	0.85	0.5	1	0.8
		Top pane	0.88	0.35	0.3	1	
Windows	North	Big	1.35	1.50	2.0	2	5.4
		Small	0.88	1.50	1.3	1	
	South	Big	1.50	1.50	2.3	2	6.4
		Small	0.63	1.50	0.9	2	

2.2.2 Stipulated general values and physical constants

Several quantities had to be determined in order to enable calculations in this study. Since exact technical information about the specific materials used in Hechengli could not be obtained, Table 2 displays stipulated values of the thermodynamic properties needed to describe the envelope elements. These properties are: heat conductivity coefficients (λ), thickness (đ), thermal resistance (R), and the heat storage correction factor (α_1).

Table 2a. Physical properties of envelope elements

Heat conductivity coefficients (λ)	W/m,K	Thickness (đ)	m
Wood (SIS, 1989)	0.14	Door	0.03
Glass (Planverket, 1981)	0.8	Door glass	0.003
Brick (SIS, 1989)	0.60	Wall	0.37
Air	—	Window	0.1
Glass (Planverket, 1981)	0.8	Window	0.003
Sawdust (SIS, 1989)	0.08	Roof	0.3
Concrete (Planverket, 1981)	1.7	Floor	0.025
Macadam	—	Floor	0.5

Table 2b. Thermal resistances (SIS, 1989)

Thermal resistances (R)	m^2K/W
Internal (R_i)	0.13
External (R_e)	0.04
Unventilated air (50–100 mm)	0.17
Macadam	1.80

Table 2c. Reduction factor (Boverket, 1993)

Red. factor due to heat storage (α_1)	
Floor	0.75

In accordance with information gathered in several interviews in Jilin in November 1999 (*e.g.* Niu, 1999-11-05; Hua, 1999-11-08), the desired wintertime indoor temperature (T_i) in rural households lies around 18 °C, even though it may vary with the time of day and drop during cold outdoor conditions. For the purpose of modelling heat demand, however, T_i is assumed to be constant at 18 °C. The air exchange rate of a building (n), is more difficult to estimate than the temperature. The general experience of interviewees seems to be that ventilation is "not a problem." Scandinavian regulations stipulate that sufficiently well blending exchange rates should amount to around 0.5 h^{-1}(Erikson, 1993), and consequently this value has been assigned to n in all calculations performed in this study. The heat recovery efficiency coefficient (η) is zero, since in general Chinese rural households are not equipped with any kind of heat recovering technology.

The density (at STP*) and heat capacity of air (ρ and c) are assigned tabulated values of 1.293 kg/m^3 and 1.00 kJ/(kgK), respectively (Ekbom, 1986). Variations with temperature and pressure are disregarded.

2.2.3 Chinese national standards

In China the base temperature (T_b) for calculating degree-days is 18 °C, and the average indoor temperature (T_{ai}) of a typical urban Chinese residential building is 16 °C. Furthermore, and in compliance with the template for the Chinese Standard for Energy Conservation Design of Civil Buildings, the so-called infiltration rate (V_{inf}) should equal either 60 or 65 % of the totally enclosed volume, depending on whether or not there are unheated stairwells in the building. Finally, the specific internal heat gain (q_{ih}) for Chinese urban residential buildings is assumed to be constant at 3.8 W/m^2 (Lang and Huang, 1993).

The figures given above have been used consistently in this study, in spite of the fact that they refer to urban rather than to rural housing. However, as the standard of living in Hechengli is high for rural Jilin, and since there are no other data available, local conditions in these respects are assumed to be comparable to urban ones. Residential buildings in Hechengli, being single-storey constructions, obviously lack stairwells. Accordingly, the entire volume is regarded as being heated, and the infiltration rate is set to 65 % of the enclosed volume.

2.2.4 Site-specific values

The site-specific parameters are those associated in one way or another with the local climate. Temperature is of course a very important parameter. By applying the degree-day concept, however, relevant and site-specific statistical temperature data can be conveniently summarised and tabulated for easy use in space-heating applications. By interpolation in a diagram by Lang and Huang, the degree-day number per heating season (D_{hs}) for Changchun can be estimated to be 4500 K·days (Lang and Huang, 1993). The same value is applied to Hechengli in this study.

Table 3. Five-day mean temperatures [°C] in Longjing, October to April 1997/98 and 1998/99 (Longjing EPA, 1999)

Date	1997/98							1998/99						
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
1–5	10.8	2.2	-11.8	-11.2	-7.5	2.2	5.5	12.3	1.1	-18.3	-12.2	-10.9	-2.7	-0.6
6–10	6.4	2.3	-9.2	-13.2	-10.2	1.1	10.2	12.0	0.0	-15.0	-14.9	-6.3	-9.4	4.2
11–15	3.9	-0.1	-13.2	-16.2	-9.5	0.2	9.4	12.5	1.8	-6.7	-10.7	-10.8	-2.8	4.8
16–20	8.1	-6.2	-10.3	-15.4	-5.0	-1.0	12.7	8.7	-8.4	-4.8	-9.8	-6.7	-1.8	9.6
21–25	3.9	-4.1	-14.5	-16.2	-3.6	2.1	15.9	8.1	-12.0	-8.4	-10.0	-2.3	-1.0	14.5
26–	0.9	-7.4	-10.4	-10.2	1.8	7.4	11.9	6.8	-7.9	-11.5	-11.4	-4.2	-0.8	11.7
Ave.	*5.5*	*-2.2*	*-11.5*	*-13.6*	*-6.2*	*2.2*	*10.9*	*10.0*	*-4.2*	*-10.8*	*-11.5*	*-7.1*	*-3.0*	*7.4*
		-6.3							*-7.3*					

* STP: Standard temperature and pressure. Denotes conditions at 0 °C and 101.3 kPa (Ekbom, 1986).

Table 3 (previous page) shows statistical temperature data for Longjing and Hechengli during the heating seasons of 1997/98 and 1998/99.

Based on these data, six five-day mean values for every calendar month from October to April have been calculated. They are displayed in Table 4 below. These values are used to represent the prevailing outside temperature (T) of Hechengli. Of course, two years is a very short period as a basis for this type of generalisation. If in the future more accurate predictions are needed than are given in this report, access to more comprehensive climate data will be necessary.

Table 4. Assumed prevailing outside temperature [°C] in Hechengli from October to April

Date	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
1–5	11.6	1.7	-15.1	-11.7	-9.2	-0.3	2.5
6–10	9.2	1.2	-12.1	-14.1	-8.3	-4.2	7.2
11–15	8.2	0.9	-10.0	-13.5	-10.2	-1.3	7.1
16–20	8.4	-7.3	-7.6	-12.6	-5.9	-1.4	11.2
21–25	6.0	-8.1	-11.5	-13.1	-3.0	0.6	15.2
26–	3.9	-7.7	-11.0	-10.8	-1.2	3.3	11.8
Ave.	*7.7*	*-3.2*	*-11.2*	*-12.6*	*-6.6*	*-0.4*	*9.2*
		-6.8 (Nov.–Mar.)					

The duration of a heating season (Z) is defined by Chinese authorities as the number of days in a year when the average daily outdoor temperature for any five successive days is lower than or equal to 5 °C (Lang and Huang, 1993). Thus, the heating season changes not only from site to site but also from year to year. In Jilin there are no officially regulated dates that define the beginning and the end of a standard heating season. Instead, it is up to the individual household or, as the case might be, central heat supplier, to determine these dates, considering the comfort level on one hand, and financial affordability on the other. For example, Changchun City Housing Heating Controlling Corporation, one of the providers of central district heating in Changchun, typically operates from 1st November to 15th April (Jiang, 1999-11-11). Based on this example and the data in Table 4, a heating season of 160 days is stipulated as computational input for this study: from the beginning of November until the end of March (151 days) allowing for a few extra days at either end of this interval*.

The average outside temperature during a heating season (T_{ave}) also varies, of course, from year to year, as illustrated by Table 3. In this study an average value is used, based on the temperatures from November to March for both seasons displayed in the table. The resulting temperature, which is slightly colder than –6.8 °C, suggests a winter climate in Hechengli statistically similar to Changchun's, where, according to Chinese national statistics, the mean temperature during the same annual interval is –6.9 °C (CSY, 1998).

Determining the dimensioning outside temperature, or DOT, requires careful attention as it involves judgement, which will influence the need for technical installations (and cost) as well as the comfort level of the residents. When temperatures drop below the DOT, this means that the heating system is no longer able to sustain normal indoor temperatures in the homes of its customers, even when operating at maximum power. To completely avoid such situations, the only way is to let the DOT equal the local extreme outdoor temperature, EOT, which is the coldest temperature that will actually occur at the location in question. Table 5 (next page) shows a range of extreme temperatures in Longjing and Hechengli from 1955 to 1998. Dimensioning

* *Cf.* the paragraph on the duration of the heating season (Z) in Section 2.1.5.

according to extreme situations, however, is usually never done in district heating, since it is too costly to invest in a facility that will hardly ever be utilised at its full capacity. In effect, a strategic trade-off is made between different costs (Frederiksen and Werner, 1993). Such an exercise falls outside the framework of this study, but in the calculations in this report a DOT of –23 °C has been used. This is also the DOT applied by Changchun City Housing Heating Controlling Corporation. According to a statistical study of data over 20 years, the actual daily mean temperature in Changchun drops below this value only five days per year, which the company considers to be an acceptable compromise in the living standard of its customers (Jiang, 1999-11-11).

Table 5. Coldest absolute outside temperatures [°C] recorded in Longjing, by decade 1955–1998 (Longjing EPA, 1999)

1955–1960	1961–1970	1971–1980	1981–1990	1991–1998
–34.8	–31.1	–30.9	–30.9	–29.1

Like temperature related data, solar correction coefficients (ε) and terms (α_{sol}) are site-specific. Available values of ε (for Changchun) and α_{sol} (for Sweden), used in solar correction computations, are presented in Table 6. There are no ε values given for single-pane windows in Changchun. Therefore, the glass panes of the doorframes in the model building are treated as double-pane balcony windows. Also, the slanted roof is disregarded, since available correction coefficients only include horizontal roofs.

Table 6. Solar correction coefficients and terms (Lang and Huang, 1993; Boverket, 1993)

Solar corr.	Window					Exterior wall			Roof	Floor	Units
	Panes	Balcony	S	N	E, W	S	N	E, W	Horizontal	—	
ε	Single	—	no data	no data	no data	0.77	0.89	0.95	0.92	1.00	—
	Double	yes	0.62	0.81	0.91						
		no	0.36	0.68	0.84						
	Triple	yes	0.60	0.79	0.90						
		no	0.34	0.66	0.84						
α_{sol}	—	n/a	1.2	0.7	0.4	0.0	0.0	0.0	0.0	0.0	W/m²K

2.3 Model output

Using data from Tables 1, 2 and 6, it is possible to calculate the heat-transmission coefficients (k) that characterise the modelled building. The results are displayed in Table 7 (next page), where the different alternatives for solar correction are clearly indicated. As a tool for comparison, the average heat-transmission coefficient (k_m) has also been included in the table. The coefficient is calculated by averaging k with regard to the envelope area (Lang and Huang, 1993):

$$k_m=\sum kA\cdot(\sum A)^{-1} \tag{13}$$

Also, a summation of specific thermal power demands due to heat-transmission losses (Π_{trans}) is presented in the table, indicating the relative dampening effect of the two solar correction methods. (For the sake of comprehensiveness and in order to enable comparisons, the calculated value of thermal power demand due to heat loss through ventilation (Π_{vent}), 28.3 W/K, is given.)

Table 7. Calculated heat-transmission coefficients and specific thermal power demand due to heat-transmission losses

Solar correction		None (ε≡1, α_{sol}≡0)	ε (ε≤1, α_{sol}≡0)	α (ε≡1, α_{sol}≥0)	n/a	None (ε≡1, α_{sol}≡0)	ε (ε≤1, α_{sol}≡0)	α (ε≡1, α_{sol}≥0)
Envelope elements		Heat-transmission coefficients, (εk) [W/m^{2}K]			Area, (A) [m^2]	Specific thermal power demand due to transmisson, (Π_{trans}) [W/K]		
Doors	N	2.60	2.47	2.60	1.3	3.3	3.1	3.3
	S		2.00		1.3	3.3	2.5	3.3
Single-pane windows	N	5.76	5.24	5.36	0.8	4.7	4.3	4.4
	S		3.57	4.56	0.8	4.7	2.9	3.7
Walls	N	1.27	1.21	1.27	22.0	27.9	26.5	27.9
	E, W		1.13		36.4	46.3	41.2	46.3
	S		0.98		20.9	26.6	20.5	26.6
Windows	N	2.88	2.42	2.48	5.4	15.5	13.0	13.3
	S		1.04	1.68	6.4	18.4	6.6	10.7
Roof		0.26	0.23	0.26	56.2	14.3	13.2	14.3
Floor		0.39	0.39	0.39	56.2	21.7	21.7	21.7
Total					207.6	186.6	155.5	175.5
Average		0.90	n/a	0.85		*Difference*	*-17%*	*-6%*

The recommended value of k_m for urban buildings in Changchun is 1.03 W/m^{2}K (Lang and Huang, 1993), which means that the modelled building is, in comparison, quite well insulated, having an average heat-transmission coefficient of only 0.90 W/m^{2}K. By Swedish standards, however, this is relatively high. Swedish regulations stipulate that k_m should be less than $0.18+0.95A_f\cdot(\sum A)^{-1}$ W/m^{2}K, where A_f equals the total area of doors and windows, as long as it does not exceed 18 % of the floor area (Boverket, 1993). Applying these conditions to the modelled building, the maximum allowed value of k_m would be 0.23 W/m^{2}K, which is a mere quarter of the figure given above. The conclusion to be drawn is that even though the requirements on living standards and comfort levels of a household in rural China may be lower than in Sweden, the specific heat demand per m^2 is not reduced correspondingly, making space heating a relatively heavy burden on the Chinese household.

Figure 3 (next page) shows a graphical representation of the results of both P(T) and Q(D) modelling, using varying indoor temperatures as input. The results are as expected: the higher the temperature indoors, the higher the power and energy demand. Using solar correction naturally reduces the predicted demand. Whereas the Q(D) model displays the highest non-corrected predictions, the P(T) models yields the highest estimates after correction. This is explained by the fact that the α method is more conservative, only allowing adjustments of the k values for windows. (For visual comparison only, the imaginary result of ε-corrected P(T) modelling is indicated in the figure.)

In order to perform a true comparison of the two models, account must be taken of the difference between effective and average indoor temperature. Referring to Section 2.2.5, T_{ai}, used in the Q(D) model, equals 16 °C, and applying Equation 12 yields a value of 17 °C for T_{ei}, given a desired indoor temperature of 18 °C. Accepting these values, the Q(D) model suggests an average household thermal demand of 4.3 kW, or 16.6 MWh per heating season. Corresponding figures for the P(T) model are 4.8 kW and 18.6 MWh. The P(T) model is also used to estimate the dimensioning thermal power demand, which is predicted to be 8.1 kW.

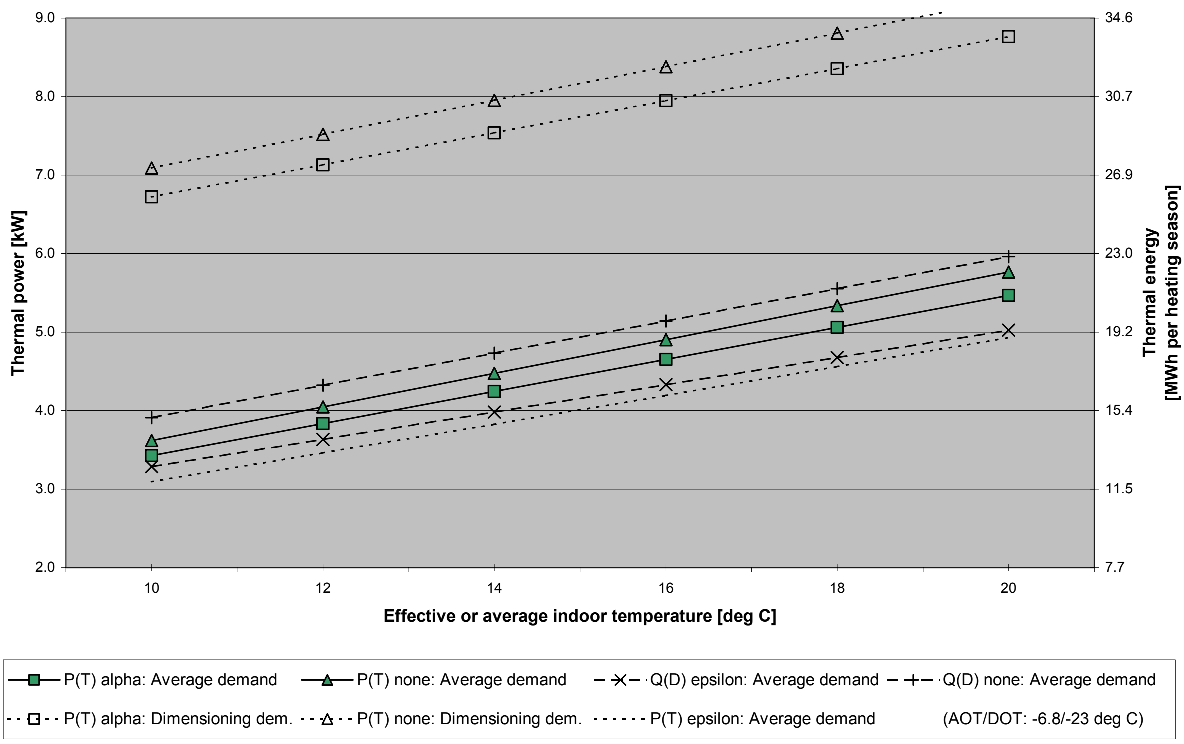

Figure 3. Thermal power- and energy-demand per household as a function of indoor temperature A comparison of the P(T) and Q(D) models including variations for solar correction computations

Although the results may seem high, in an international comparison they are not unreasonable. For comparison, the maximum thermal power demand of a single-family house in southern Sweden typically ranges between 6 and 12 kW (Norén, 1998). On one hand one might argue that demand ought to be lower in the modelled building than in Sweden, because the heated area is much smaller than most Swedish homes. On the other hand, however, winters in southern Sweden are generally considerably less severe than in Jilin. Also, the fact that the modelled building has a high average heat-transmission coefficient affects the heat demand, making it high compared with buildings with lower values of k_m.

2.4 Estimating actual annual energy usage

Having come this far in modelling, it is important to relate the results to real life. In doing this, a distinction is introduced between the concepts of *usage* and *demand*. The models described in this report are used to predict the physical heat demand of a mathematical representation of a building. As defined here, this quantity is an abstraction only, and in reality there is no method, with which to measure or determine the heat demand as such. The definition of usage, on the other hand, refers to actual cases, including conversion losses and other real-life phenomena. Therefore, it is a relatively straightforward quantity to determine or estimate. For many reasons, de-facto usage differs from modelled demand. For example, there is a mismatch due to the fact that a real, technical energy supply system always has an efficiency coefficient less than one, causing usage to be greater than demand. Ideally, the magnitude of both usage and efficiency are known, enabling an empirically based estimate of the size of the demand to be made. However, the discrepancy can partly be explained by model simplifications and imperfections, or errors in the values of input parameters. A serious limitation of the models used in this study is that they are static in relation to the behavioural dynamics of the residents. Experience shows that energy usage due to different habits and behaviour of residents can differ by as much as 1:3 between houses that, from a model perspective, are identical and thus have the same calculated heat demand (Andersson, 2000-02-09).

Another practical problem when dealing with actual figures for energy usage in northern rural China is the difficulty in separating the fractions used for cooking and heating. As a starting point for an analysis, it may be presumed that cooking is normally performed to approximately the same extent every day of the year whereas heating, on the other hand, is only required wintertime. Such an assumption can be used in an attempt to differentiate between the different streams of energy. It is important to bear in mind though, that much of the energy used for cooking contributes to the heating of ambient space. In summertime this "cooking heat" is wasted, as it has to be ventilated away, whereas during the heating season it contributes to meeting the general heat demand.

Households in rural Jilin normally do not have running hot water, even when connected to a communal tap-water system. The heating of water for drinking, personal hygiene, and washing of clothes is generally performed on the stove, and the hot water is stored in thermos flasks. Similarly to food, the demand for hot water is assumed to be rather stable over the year, and unless specifically commented upon in the following discussion, it is included as a sub-item in the energy usage during cooking.

Because of the various difficulties of empirically determining or estimating *demand*, the following discussion focuses instead on the presentation and comparison of different estimates of the annual *usage* of energy for rural residential space heating in Jilin.

2.4.1 Modelled estimate

As previously stated, the modelled annual thermal energy demand ranges between 16.6 and 18.6 MWh per household, depending on whether P(T) or Q(D) modelling is employed. To obtain a rough corresponding estimate of the thermal energy usage, one only has to divide these values by the appropriate efficiency factor.

The value of this factor may, however, vary considerably, depending on how it is defined and the conversion technology employed. In this particular context, the utilised fuel's energy content, expressed as its lower heating value, is considered to be the reference quantity. No previous treatment or transportation of the fuel is included. The efficiency factor reflects the share of this energy that is successfully transformed into useful space heat within the household, neither being lost as thermal energy in the flue gases, nor wasted due to incomplete combustion and emitted as combustible chemical compounds.

The traditional way to supply space heat in rural homes in Jilin is by using a kang. Whereas modern solid-fuel-fired underground kangs (so-called "energy-saving" kangs) can operate at an efficiency exceeding 50 % (Cao *et al*, 1998), there are also indications that traditional kangs, when heated with gas burners, can be up to 70 % efficient (Henderick, 2000). A heating system such as Mr Hua Jisheng's in Hechengli, where hot-water radiators are combined with kang-based flue-gas heat utilisation, can probably perform better still, perhaps achieving as much as 90 % efficiency (Hao, 1999-11-12). For district-heating systems, efficiency can be said to be 100 %, since the delivered input energy, which is already in thermal form (not stored chemically in any kind of fuel), is entirely transferred to the household as space heat.

A probable future alternative to district heating in Hechengli is the same type of radiator–kang combination already used by Mr Hua, replacing, however, solid fuel by gas from the gasification plant. In such a case, assuming the efficiency to be as high as 90 % in light of the brief discussion above, the models presented in this report yield an estimated thermal energy usage in Hechengli spanning from 18 to 21 MWh per household per year.

2.4.2 Conventional wisdom

There are no externally accessible investigation reports that supply first hand information about the actual heat usage or demand of rural households in Jilin, in which the separation of cooking and heating applications has been attempted. Among Jilin experts in the field of provincial rural energy systems, however, there exists a widely spread and well-established common opinion in this matter, based on experience. The view is that, as a rule of thumb, one third of the annual thermal energy usage is the result of cooking and the remaining two thirds are accounted for by the need for space heating (Jia and Qiang, 1999-11-04; Liu, 1999-11-07; Hao, 1999-11-12).

As an illustration, the following example, based on the use of gasified agricultural residue as the sole energy source, gives an idea of the orders of magnitude that are at hand. The gas referred to is produced by the gasification plant in Shijiapu, which was the first plant to be built as a result of the biomass-oriented commitment to rural energy of the leadership of Jilin. The gas has a heating value of only about 1100 kcal per m^3 (which is equivalent to 1.3 kWh or 0.16 kgce per m^3). A rural household of 5 persons is expected to need between 5 and 6 m^3 per day of this gas for cooking, corresponding to an annual energy usage of 2 to 3 MWh (a portion of which contributes, of course, to wintertime space heating). These figures, also cited in a report by Jilin Province Energy Resources Institute, are based in part on experience from Shandong Province (Liu, 1999-11-07; JPERI, 1998). In Jilin, local estimates of gas usage solely for the purpose of wintertime heating range from 15 or 18 m^3 per day (JPERI, 1998), through 25 m^3 (Jia and Qiang, 1999-11-04; Liu, 1999-11-07), up to 40 m^3 per day (JPERI, 1998). Assuming a heating season of 160 days, the annual energy usage for space heating may then be expected to fall between 5 and 8 MWh, based on 25 m^3 and 40 m^3 as average daily gas consumption, respectively. Thus, according to established Chinese estimates, the total annual thermal energy usage of a rural household in Jilin ought not to exceed 11 MWh.

2.4.3 Statistical estimate

According to official Chinese statistics, gross energy usage by the rural residential sector in Jilin in 1996 exceeded 62 TWh, or the equivalent of 4 MWh per person (see Table 8, next page). These figures include electricity but not petroleum-based energy carriers such as oil, petrol or diesel, which presumably are fuels used mainly for transport. It may therefore be considered that, apart from the energy needed for generating electricity, the energy accounted for in the table was predominantly used for cooking and wintertime space heating of households. The energy used within the rural residential sector for heating of spaces other than people's homes, such as outhouses, is assumed to be negligible. Seeing that the average number of permanent residents in a rural Chinese household in 1996 was 4.42 (CSY, 1998), this implies that a statistically normal household in rural Jilin might use roughly 16 to 18 MWh annually for cooking and space heating combined. Assuming that cooking requires the better part of 3 MWh (see Section 2.4.2), this leaves at least 13 to 15 MWh exclusively for heating. The result, of course, is only a rough estimate of the average usage with no specification of the standard deviation.

Table 8. Residential energy usage of the rural population in Jilin, by source, 1996 (CREY, 1997)

Energy source	Amount		Gross energy equivalent		Specific energy use	
		unit	×1000 tce	TWh	kgce/person	kWh/person
Stalk residue	8220.2	×1000 t	3526.5	28.69	235.0	1912
Firewood	2818.6	×1000 t	1609.5	13.10	107.2	873
Raw coal	2943.2	×1000 t	2101.6	17.10	140.0	1139
Electricity	845	GWh	338.2	2.75	22.5	183
Petroleum	no data	×1000 t	—	—	—	—
Gasified biomass	2414.8	×1000 m^3	1.8	0.01	0.1	1
LPG	33642.7	×1000 m^3	57.7	0.47	3.8	31
Natural gas	2752.8	×1000 m^3	3.7	0.03	0.2	2
Coal gas	3420.0	×1000 m^3	2.0	0.02	0.1	1
Solar	672.7	×1000 m^2	—	—	—	—
Total			7641.0	62.17	509.1	4143

2.4.4 Computed estimate

As a final attempt to comment on the actual usage of thermal energy in rural households in Jilin, reference is made to Mr Hua Jisheng of Hechengli, on whose household the mathematical models are based. Knowledge about his annual consumption of coal constitutes a foundation, from which an estimate of energy usage for space heating can be computed. The coal is used for cooking, of course, as well as residential space heating, but also for wintertime heating of a combined rabbitry and pigeonry, which is located in the eastern part of the storage building opposite the residence. According to calculations and estimates, which are presented in detail in Appendix A, the energy usage of Hua's household for space heating can be separated into 9 MWh and 17 MWh for the outhouse and the residence, respectively.

2.4.5 Comparison of estimates

In all the estimates of energy usage per household presented in this report, the rather generous value of 3 MWh is chosen as the standard quantity required annually for cooking, even though it is clear that some of this energy contributes to heating as well. The reason for this is the attempt to avoid underestimating the relative importance of cooking compared with space heating. Still, whereas conventional wisdom among experts in Jilin suggests that cooking represents about one third of the total energy usage, all other estimates imply that, in fact, the proportion does not exceed 20 %, see Table 9. More detailed discussion about the questions that arise in regard to the relationship between energy for heating and cooking in Jilin are, however, left for future studies in this area.

Table 9. Comparison of estimates of annual energy usage for space heating and cooking per rural household in Jilin

Annual usage	Heating [MWh]	Cooking		
		[MWh]	compared to heating	share of total usage
Modelled estimate	18 – 21	3	1:6.0 – 1:7.0	13 – 14 %
Conventional wisdom	5 – 8	3	1:1.7 – 1:2.7	27 – 38 %
Statistical estimate	13 – 15	3	1:4.3 – 1:5.0	17 – 19 %
Computed estimate	17	3	1:5.7	15 %

The data in Table 9 show that local experts' opinions on the actual magnitude of rural residential energy usage for space heating in Jilin differ considerably from the other estimates made in this report. For example, it falls significantly short of the statistically based estimate of average household usage in the province, being about half. Noting that no assumptions have been made about the standard deviation of the estimate, knowing also that the standard of living in the countryside may vary considerably, it is conceivable that some households in rural Jilin manage to uphold their customary comfort levels on a very low energy usage. In the light of the other estimates, however, it seems improbable that these figures are representative for the majority of Jilin's rural population.

As for the energy usage of households in Hechengli, which is a fairly prosperous village, it is natural that it should exceed the average for rural Jilin as a whole. Judging from the figures of Table 9, this also seems to be the case. The computed estimate, based on Mr Hua's household, yields a higher energy usage than the estimate made from statistical data.

The highest estimate is the modelled one, which may not be surprising considering the temperature conditions incorporated into the model. It is unrealistic to assume that the residents of a rural village like Hechengli will actually maintain an indoor temperature of 18 °C all through the heating season, 24 hours a day, irrespective of the climatic conditions outside and the time of day. As can be seen in Figure 3, the heat demand is quite sensitive to temperature changes. A decrease in the steady indoor temperature of 4 °C leads to a decrease of 3 MWh in annual thermal energy demand. The effect on usage will be even greater. Other factors that can help explain why the modelled estimate is comparatively high include (i) model simplifications, such as the fact that the outer roof has been disregarded, and (ii) the complete oversight of residents' behaviour, such as measures to reduce drafts and heat transmission at doors and windows in wintertime by sealing cracks and adding extra insulating layers of air using plastic, wooden or metal covers, *etc.*

In order to obtain an additional perspective in evaluating the reasonableness of the different estimates in Table 9, an international comparison may be of interest. According to Swedish statistics for one- and two-dwelling buildings, houses that exclusively use oil for space heating typically consume 22 litres of oil annually per m^2 heated area (SCB, 1998). At about 0.84 kg/litre and 42 MJ/kg (Alvarez, 1990), and a heated floor area of 56 m^2, this figure implies an equivalent of 12 MWh per year for a building the same size as the one modelled. Making corrections for the difference in average heat-transmission coefficients between the modelled building and residences in Sweden (refer to Section 2.3), a comparative value of 43 MWh per year is obtained. It is clear from this admittedly rough figure that although the modelled estimate of energy usage given in Table 9 may seem exaggerated in a Chinese context, it is in no way unreasonably high.

Before moving on, it is important once again to stress that the figures discussed in this section are estimates of usage, not of demand. In relation to what a statistical household in rural Jilin may actually achieve, the efficiency factor of 90 % used to calculate the modelled estimate of usage is very high. Therefore, if the comparison had been made between values of demand rather than of usage, the difference between the modelled estimate and the others would have been even greater than indicated. Even so, subsequent calculations will be based on the relatively high, modelled figures. This can be motivated from at least three perspectives:

- If a decision is made to introduce district heating in Hechengli, it is better to overestimate than underestimate demand, since it is important not to invest in a system that is under-dimensioned from the start.
- The order of magnitude of the modelled demand is reasonable for similar conditions in, for example, Scandinavia. Even though the present, and in comparison relatively low, standard of living in rural China contributes to keeping down the heat demand of households, future demand may be expected to increase as the standard of living increases (disregarding the scope for measures such as adding insulation to reduce energy demand).

- There are no other, comparably well founded or scientifically estimated figures to use.

2.5 Estimating the heat load of a district-heating grid in Hechengli

The load of a district-heating grid is a measure of the gross amount of heat that has to be fed into the grid in order to satisfy the demand. Therefore, in estimating the heat load it is necessary to first determine the magnitude of the loss due to distribution. Although this study does not include any detailed calculations, a mathematical description helps to show to what extent different parameters actually affect distribution loss. The following description applies to buried, parallel, individually insulated pairs of pipes, as illustrated in Figure 4. The pair consists of a supply pipe, in which hot water is transported to the customers, and a return pipe, in which the same water, at a lower temperature, returns to the plant.

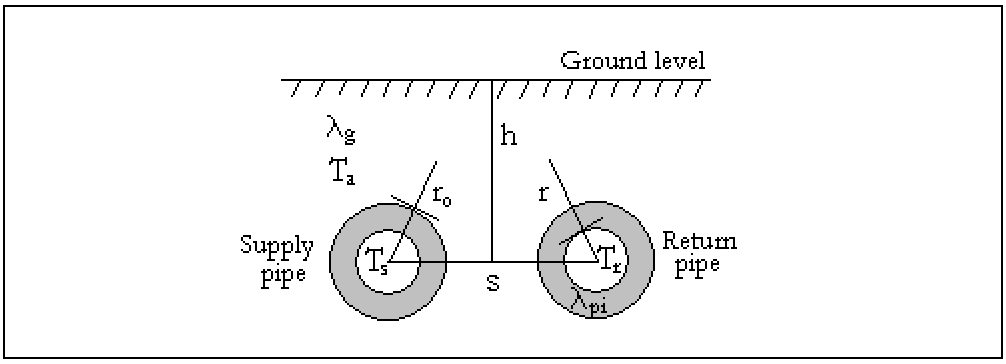

Figure 4. Buried parallel, individually insulated pair of pipes

2.5.1 Rate of heat loss

Heat loss from the distribution grid occurs because of temperature differences between the pipes and the ground. For separate, parallel pipes the loss rate can be expressed as (Frederiksen and Werner, 1993):

$$P=P_{sa}+P_{ra}=2\pi rLR^{-1}\cdot(\theta_{sa}+\theta_{ra}) \quad (14)$$

where $\theta_{\bullet a}=T_{\bullet}-T_a$ (15)

P_{sa} = power dissipation from the supply pipe to the ground	[W]
P_{ra} = power dissipation from the return pipe to the ground	[W]
r = inner radius of pipe	[m]
L = length of the pipe pair (*i.e.* half the total pipe length)	[m]
$\theta_{\bullet a}$ = temperature difference relative to ground	[K]
T_s = temperature of supply pipe medium	[°C]
T_r = temperature of return pipe medium	[°C]
T_a = temperature of ground	[°C]

Here, the thermal resistance (R) consists of three major constituents, namely:

$R=R_g+R_{pi}+R_{tz}$ where (16)

$$R_g=r\lambda_g^{-1}\cdot\ln(2h/r_o) \quad (17)$$

$R_{pi}=r\lambda_{pi}^{-1}\cdot \ln(r_o/r)$ and (18)

$R_{tz}=r\lambda_g^{-1}\cdot \ln(4h^2s^{-2}+1)^{½}$ (19)

R_g = ground resistance	[m^2K/W]
R_{pi} = pipe insulation resistance	[m^2K/W]
R_{tz} = resistance due to coinciding temperature zones	[m^2K/W]
λ_g = heat conductivity coefficient of the ground	[W/m,K]
λ_{pi} = heat conductivity coefficient of the pipe insulation	[W/m,K]
h = distance between pipe's centre and ground level	[m]
r_o = outer radius of pipe including insulation	[m]
s = distance between centres of the two pipes	[m]

For well-insulated pipes (*i.e.* λ_{pi} is low or r_o»r) the insulation resistance (R_{pi}) is by far the most dominant term. However, in China today, district-heating pipes are often poorly insulated (*i.e.* λ_{pi} is high or $r_o/r\rightarrow 1$) (Jia and Qiang, 1999-11-04). This increases the importance of the ground resistance (R_g), the value of which it is far less practical to influence or vary than insulation. The third resistive component, resistance due to coinciding temperature zones (R_{tz}), is normally of little significance compared with the other two (Frederiksen and Werner, 1993).

2.5.2 Total heat loss per season

The usual way of expressing the magnitude of the accumulated heat loss (Q_{loss}) during a year or a heating season is as a percentage of the total amount of thermal energy that has been supplied to the grid (Q_{supp}). The expressions above, although informative when discussing the reasons for distributive heat loss, cannot easily be used to estimate such figures. Instead, it is more convenient to isolate four grid properties that determine the size of the loss. These are *insulating capacity* and *dimensions* of the pipes, *temperatures*, and the *geographic concentration* of the heat demand. Quantities that can be used to describe these factors are (Frederiksen and Werner, 1993):

R_m = average thermal resistance in the grid	[m^2K/W]
r_m = average inner radius of grid pipes	[m]
$\int\theta_{ma}dt$ = degree-time number for heat distribution	[Kh]
H = heat density of the grid = Q_{del}/L	[Wh/m]
Q_{del} = heat delivered by the grid	[Wh]
Q_{supp} = heat supplied to the grid	[Wh]
Q_{loss} = heat loss	[Wh]

Because properties vary between locations within the grid, mean values (denoted by the subscript "$_m$") are used. The mean temperature of the grid medium (T_m) is calculated as the mean value of supply and return pipe temperatures. Using these quantities, the heat loss can be expressed by the following equations (Frederiksen and Werner, 1993):

$Q_{loss}=2\cdot LR_m^{-1}\cdot 2\pi r_m\cdot\int\theta_{ma}dt$ or (20)

$Q_{loss}/Q_{supp}=(1+½\cdot R_mH/(2\pi r_m\cdot\int\theta_{ma}dt))^{-1}$ (21)

It can be seen from these expressions that high thermal resistance (*i.e.* well-insulated pipes), a high heat density, and low grid temperatures help to reduce distribution loss. The way in which pipe dimensions affect the loss is more complicated to describe (since R=R(r)). The value of loss quotients (Q_{loss}/Q_{supp}) varies considerably between different district-heating grids, and it is difficult to say what is "normal." For Scandinavian grids serving single-family houses in residential areas, where the settlement structure is similar to Hechengli's, values can range between 10 % and 30 % (Frederiksen and Werner, 1993). If technology with properties equivalent to Scandinavian standards are used, it is reasonable to assume that a possible future district-heating grid in Hechengli will have a loss quotient of similar magnitude.

As a worst-case scenario, considering the loss quotient of a non-insulated grid with pipes buried just under ground level may be of interest. The following assumptions have been made to obtain such a value for Hechengli:

- Ambient ground temperatures equal air temperatures as given in Table 4, and the heating season lasts from 26th October to 5th April.
- The heat delivered by the grid equals the average thermal energy demand of the village as calculated from the solar-corrected P(T) model.
- Ground resistance is the only thermal resistance accounted for, and the heat conductivity coefficient of the ground (λ_g) is assumed to be 1.5 W/m,K (*cf.* Løgstør Rør, 1997). Standard values for λ_g range between 1.0 and 1.8 W/m,K in normal earth, which is neither too solid nor too moist (Andersson, 2000-02-09).
- Grid medium temperatures are 80 °C and 60 °C in supply and return pipes, respectively, and the total length of the pipe pair grid is 11 380 m (as proposed and motivated in following sections of this report, together with other characteristics of a possible district-heating grid in Hechengli).

Employing Equation 21, the resulting loss quotient from this theoretical experiment equals 96 %, which further emphasises the importance of adequate pipe insulation.

2.5.3 Representations of estimated heat load

Figure 5 (next page) shows the expected heat demand of Hechengli from October to April, together with the corresponding heat load of fictive grids with static loss quotients of 10 % and 30 %. The demand is calculated using solar-corrected P(T) modelling of a single household with input parameters as described in previous sections of this report, multiplying the result by 224 households to represent the whole village. For district heating, the coefficient of efficiency between demand and usage is regarded as being 100 %.

For engineering purposes, load curves such as those in Figure 5 are normally supplemented or replaced by so-called load duration curves. These are diagrams where days are displayed in consecutive order according to the magnitude of thermal power, from greatest to least, instead of chronologically. The advantage of this type of representation is that the total amount of time, during which a certain power level is exceeded annually, can easily be seen (Frederiksen and Werner, 1993). Figure 6 (next page) shows duration curves where the contents of the load curves in Figure 5 have been rearranged. Because the temperature data, which have been used to model these estimates, consist of five-day means (*cf.* Tables 3 and 4), there is an inherent equalisation that hides the actual day-to-day variation. The result is an unusually smooth curve, which in general ought to have a steeper profile and, in particular, a more distinct and spiky appearance at its left end. In trying to compensate somewhat for the effects of insufficient resolution, the loads at the postulated dimensioning outside temperature (–23 °C) have been indicated on the power axis.

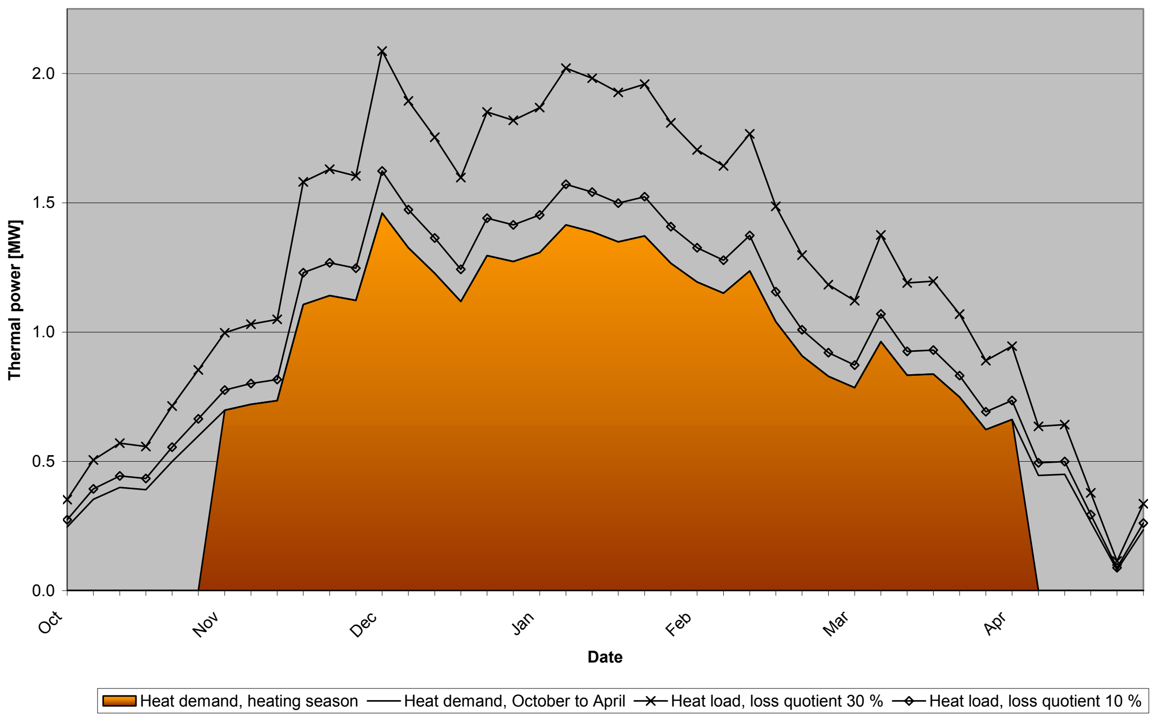

Figure 5. Modelled heat demand of Hechengli and the corresponding heat load of two fictive district-heating grids with different loss quotients

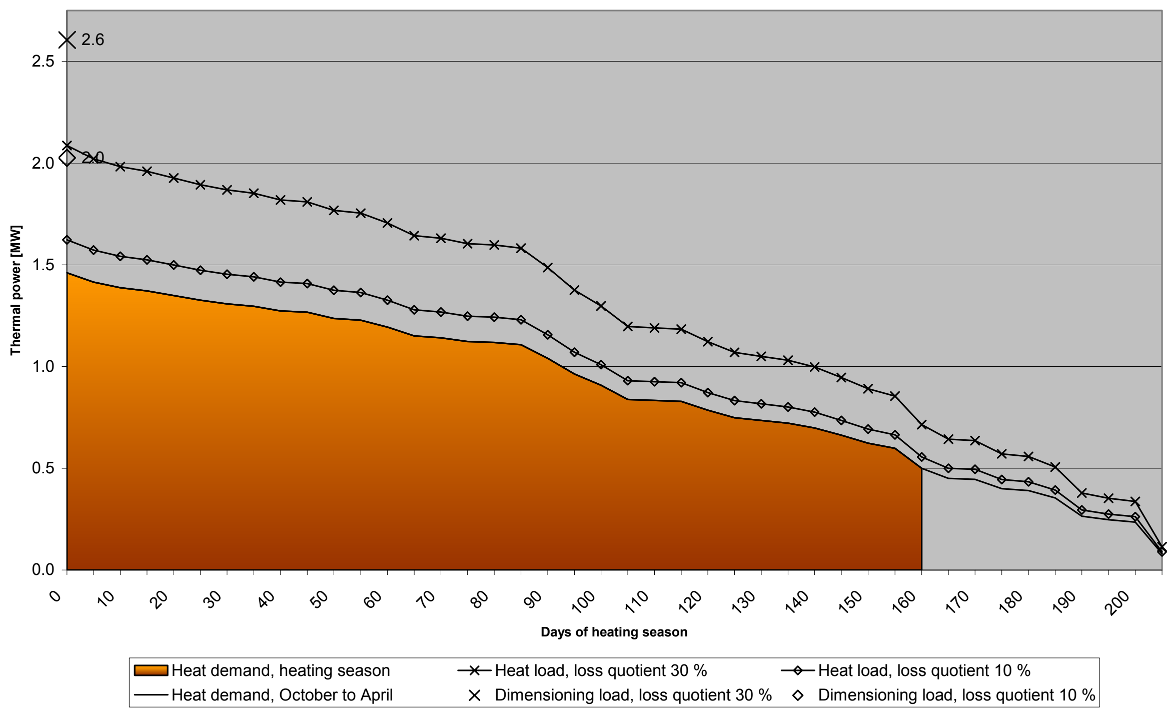

Figure 6. Duration curves of the modelled heat demand of Hechengli as well as of the corresponding heat load of two fictive district-heating grids with different loss quotients

A third but not as illustrative a way of representing the estimated heat load is presented in Table 10.

Table 10. Modelled heat demand of Hechengli and the corresponding heat load of two fictive district-heating grids with different loss quotients

Case	Model (solar corrected)	Demand (usage) [MW]	Heat load [MW]	
			10 % loss	30 % loss
Dimensioning	P(T), α	1.8	2.0	2.6
Heating season average		1.1	1.2	1.6
	Q(D), ε	0.97	1.1	1.4

2.6 Significance of estimated load

The issue of the significance of the heat load of Hechengli, as it is estimated and presented in this report, can be viewed from at least two different perspectives. Foremost, in a general perspective there is the question of how the estimates of demand and usage are related to reality, now and in the future. It is equally important to discuss, however, how they influence and fit into the other parameters and constraints of the biomass gasification project. For the decision-making process of whether or not to invest in district heating, these aspects are crucial.

2.6.1 Future changes to present heat demand

There are several parameters that influence the way heat demand may change in Hechengli. Better insulated houses could cut household demand considerably. Table 7 indicates that the greatest heat losses occur through transmission through walls and the floor, suggesting that these areas ought to be addressed first if such measures were to be taken. Today, no building regulations apply to houses in rural Jilin (Li, 1999-11-08), but by spreading awareness about the situation and what measures can be employed to improve it, voluntary incentives may still have an effect on the heat demand of Hechengli as a whole.

Other factors, which may follow due to improvements in the general standard of living, may turn out to counteract the possible decrease in demand achieved through additional insulation. Adding a hot tap-water supply, for example, would most likely cause an appreciable increase in demand. Also, a higher standard of living may cause residents to require more stable and higher indoor temperatures than at present, thus influencing demand.

It is important not to forget in this discussion the consequences for the aggregated heat demand that would follow any change in population in Hechengli.

2.6.2 Available thermal power from electricity production

In a study addressing the technical aspects of gas turbines in the context of the Hechengli project, Paul Henderick of Princeton University suggests that a 75 kW_e microturbine would be more than sufficient in meeting the local need for household electricity (assuming 100 households in the village), even at peak demand. There would be enough capacity to supply power also to local industries or to the electric grid (Henderick, 2000).

When operating at full electric output such a turbine should yield some 140 kW_{th} of hot water, given water temperatures at the inlet and outlet of the exhaust-cooling heat exchanger of 50 °C and 83 °C, respectively, and a water mass flow of 1.0 kg/s (Henderick, 2000). Presumably, more thermal power could be made available by decreasing the share of the electric power output. Not all of the available power is necessarily usable, however. Assuming, first, that the flow remains unchanged and, second, that the temperature difference actually utilised for space heating amounts to only 20 K (*cf.* Section 3.4), the following result may be argued for. Since the delivered power is proportional to the temperature difference (*cf.* Equation 23 in Section 3.5.2) the portion of the turbine's thermal output that in effect is distributed to the households equals approximately 60 %, or 85 kW_{th}. The extent to which the relatively wide margin between available and usable thermal power can be considered to cover distribution losses has to be discussed in a context that takes into account the temperature restrictions of the grid medium.

Table 11 serves to illustrate the extent to which one 75 kW_e microturbine might contribute to the average thermal power demand of a single household, and to that of three different-sized grids covering 84, 112 and 224 households.

Table 11. Estimated contribution, given two alternative supply capacities, to the modelled average thermal power demand of a single household and of three different-sized district-heating grids

	Average power demand [kW_{th}]		In proportion, 140 kW_{th} can contribute		In proportion, 85 kW_{th} can contribute	
	P(T) α	Q(D) ε	P(T) α	Q(D) ε	P(T) α	Q(D) ε
1 hh	4.8	4.4	2920 %	3180 %	1770 %	1930 %
84 hh	403.2	369.6	35 %	38 %	21 %	23 %
112 hh	537.6	492.8	26 %	28 %	16 %	17 %
224 hh	1075.2	985.6	13 %	14 %	8 %	9 %

According to Henderick's report, 140 kW_{th} would suffice to provide enough thermal energy to meet an "average winter heat demand" of 100 households at merely 1.2 kW per household, allowing for a distribution loss of 14 %. In addition, however, Henderick notes that an insulated household, basically equivalent to Mr Hua's in Hechengli, is likely to require in excess of at least 3.2 kW in order to compensate for heat loss (assuming temperatures of 15.6 °C indoors and –7.4 °C outdoors) (Henderick, 2000). These statements are not consistent, but the latter agrees with the findings of this report, where the modelled average thermal power demand amounts to some 4.4 to 4.8 kW per household. Once it is known what thermal capacity the plant in Hechengli will actually have, more detailed calculations can be performed.

2.7 Possible strategies for district heating in Hechengli

It is implied in Section 2.6.2 that the proposed facility for gasification and electricity production in Hechengli might not be sufficient to supply more than a fraction of the average thermal power demand of the village. The ability of the demonstration plant to respond to the load situation of a possible future district-heating grid will naturally influence the design of the entire system, which, regardless of the capacity of the base-load supply unit, will have to rely to a greater or lesser extent on auxiliary and peak-load supply equipment. There are three principal strategies by which to approach the establishment of a district-heating system in Hechengli. In this report they are called the extensive direct approach, the phased expansion approach, and the limited direct approach.

The extensive direct approach means that pipes and other equipment are installed in one step to cover the entire village, and that all 224 of Hechenli's present households are connected to the grid. The advantage of this approach is that by carrying out all installations in one sweep, costs can be reduced to a minimum. Also, the increased comfort level offered to residents through a central heat supply will benefit the entire village and not just parts of the community. On the other hand, all investment costs must be borne at the same time, requiring a large amount of disposable capital. Another disadvantage is that if base-load heat supply from the trigeneration plant is scarce, it may not be able to contribute very much to the total load of an extensive grid. The need for supplementary capacity may turn out to be considerable, making necessary further concurrent investments for the installation of even more equipment.

By adopting the phased expansion approach, the extent of the disadvantages of extensive direct installation of district heating can be reduced. At the same time, the door is left open for future extensions of the system in order to provide for a general raise in living standard. In practical terms this strategy means that system design is performed to encompass the entire village, although only parts of the total installations are completed in the first phase. This approach is the most versatile one, but it has to be bought at the price of additional costs due to initial over-dimensioning, *etc*. If the initially available supply capacity is limited, however, it is a strategic way of making good use of it while awaiting an expected expansion.

In choosing the limited direct approach, the grid is designed to encompass only part of the village, thereby enabling an optimised match between supply capacity and expected load. The option to expand the system remains, of course, but will require greater future costs to be borne for design and installation than if provisions for an expansion were made from the start.

Since there is not enough information available yet to enable concrete conclusions to be drawn about the technical nature and capacity of the future plant in Hechengli, in this report it is assumed that an adjoining district-heating system will be built in accordance with the phased expansion approach. In order to facilitate comparisons, three different fictive grid sizes are considered, namely the same ones that are indicated in Table 11. These encompass 84, 112 and 224 households, corresponding to 38 %, 50 %, and 100 % of the village, respectively.

3. District-heating technology

3.1 General characteristics

A district-heating network can be separated into three functional parts: the production circuit, the distribution grid and the end-user circuits. In terms of technical considerations, this report focuses mainly on the distribution grid, intending to give an idea of the main issues that need to be addressed when dimensioning a small-scale district-heating system, using Hechengli as a reference and example. The production and end-user circuits receive no separate attention from a technical point of view, other than when they directly interact with the grid.

In order to better illustrate the general technical aspects of a district-heating grid, commented on in this report, they will be applied to an imaginary grid as illustrated in Figure 7.

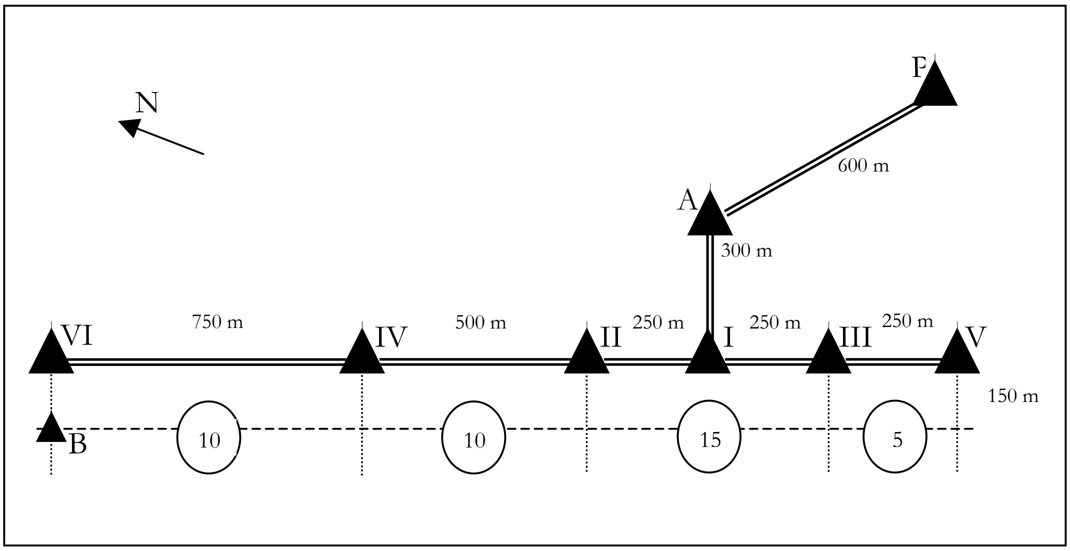

Figure 7. Proposed district-heating grid in Hechengli

The figure roughly indicates what a future grid in Hechengli might actually look like when fully developed to encompass all of its households. Three nodes labelled P, A, and B have been marked together with six nodes numbered I to VI using Roman numerals. Node P signifies the location of the gasification plant, and node A marks the location of the nearest possible customers, namely the Hechengli poultry and fertiliser plants. Since in this study the conditions and possibilities for industrial district heating are not investigated, no further attention will be paid to this topic. Node B shows the position of the most remote customer of the proposed grid.

The part of the figure where nodes are numbered represents the section of the grid that runs parallel to the village main street. This is the grid's main branch, and the part running between the plant and the street (between nodes P and I) is called the feed branch. The main branch forks into several side branches (not indicated in the figure) leading into the alleys where the homes of the residents are located. Side branches, in turn, fork at every household into service branches that constitute the final link in the heat-distribution system.

Since there is no map of Hechengli available showing the exact locations of alleys and households, all further discussions about the Hechengli grid are based on the following assumptions. There are 40 alleys, distributed at variable distances along the main street as is illustrated by the numbers in circles in Figure 7. On average, an alley is 100 m long from the main street to the final household. The maximum distance is 150 m, and the number of households in a row never exceeds seven. Service branches connect to households from the north, across their back yards, not exceeding 12 m in length.

3.2 Direct and indirect systems

An issue of fundamental concern for a discussion about applied district heating is the nature of the interfaces between the distribution grid on one side, and the production and end-user circuits on the other. The interfaces can belong to one of two types: direct or indirect. In a direct connection, the same physical medium flows on either side of the interface. In an indirect connection, the circuits are separated by heat exchangers, which is why, technology-wise, it is more sophisticated than a direct one. Both systems, however, have their own advantages and disadvantages. The principal structure of an indirect system is illustrated in Figure 8.

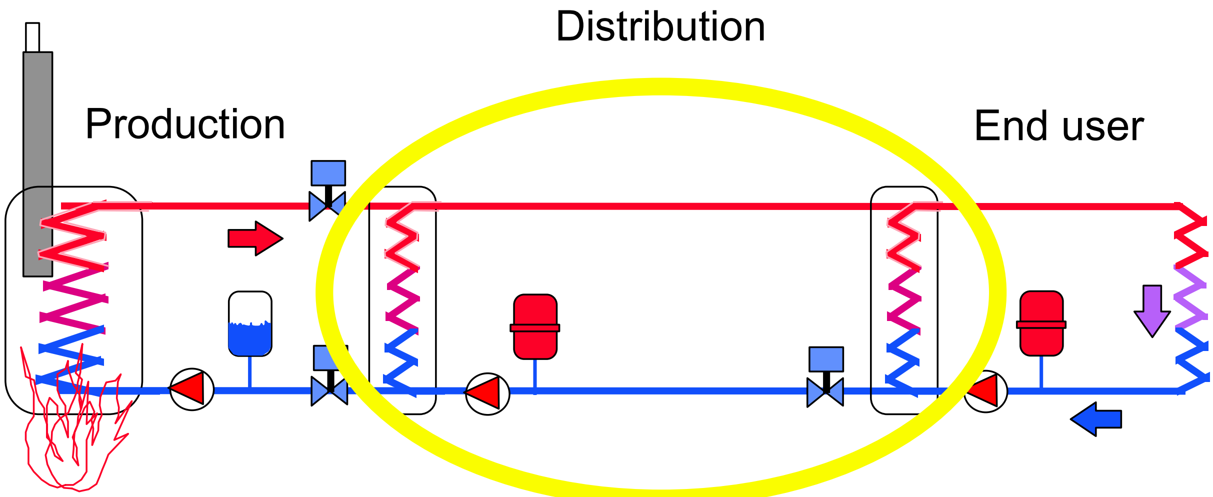

Figure 8. Principle sketch of an indirect district-heating system showing the distribution grid with heat exchangers at the interfaces to the production and end-user circuits
(Picture by Per Lidell, Alstom Power Flowsystems.)

Compared to an indirect system, a direct system is technically simpler and the investment less costly. At the same time, it is more vulnerable to leakage which, if it occurs, will influence the entire system. Radiators in the end-user circuits are often sensitive to pressure peaks that may propagate through the system due to valves closing, pumps starting or pipes breaching in other locations. Closed end-user circuits in an indirect system can decrease these risks. Corrosion is another potential problem, which is more difficult to deal with in a direct system, and which may cause leakage. In terms of operating conditions, indirect systems are more versatile in the sense that temperature, flow and pressure levels need not be the same in the three system components (Frederiksen and Werner, 1993).

For the proposed grid in Hechengli, this report will henceforth assume a direct system. The reason is that cost and simplicity are thought to be of more decisive importance to the project management in this case than technical sophistication.

3.3 Hot-water supply

In Scandinavia, central heating almost always includes the supply of hot tap-water. In China, the situation is different, and in rural areas such as Hechengli, families usually heat whatever water they need for washing, hygiene or drinking on their stoves, storing it in thermos flasks. The effect on hot-water demand in rural China, if convenient and easily accessible grid-heated water were made available, might be considerable. An evaluation of such a scenario is not included in this study, but might very well be the topic of a separate investigation.

Experience from previous district-heating projects suggests that when located in areas where customers do not enjoy access to hot tap-water, systems for central heating may suffer problems due to tapping. Instead of heating their own water, some residents tap hot water from the communal radiator circuit, which leads to a decrease in the lifetime of the equipment. The problem, which is especially difficult to overcome in direct-connection systems, where locating it may be extremely laborious, is also known in China. As preventive measures, apart from installing indirect systems with small and controllable end-user circuits, two options are suggested by people in the industry. Including hot tap-water supply in the concept is the most progressive strategy. An alternative is to dye the water in order to make people less prone to use it (Lidell, 1999-08).

3.4 Temperature levels

District-heating systems have to be designed according to the proposed temperature levels of the medium in the distribution grid. Depending on expected load cases, it is possible to determine optimal levels from a thermodynamic point of view. Universal optima, however, generally do not exist. In any case, it is rare that mathematical load optimisations influence the choice of temperature levels much. Instead, tradition, national standards, and other practical considerations outweigh the importance of detailed calculations. Another aspect, which it is important to keep in mind when discussing temperature levels, is that temperatures in both supply and return pipes may be allowed to vary considerably within a grid depending on the operation conditions. Also, the term “temperature level” is not unambiguously defined, as it can be used to denote either maximum or average temperatures (Frederiksen and Werner, 1993).

A rough way to characterise grids according to temperature levels is to separate them into high- and low-temperature grids. The borderline can be drawn between grids that allow maximum temperatures exceeding 100 °C and those that do not. High-temperature grids generally require special safety regulations and stricter controls, especially where hot-water pipes enter buildings or other confined spaces. Since at atmospheric pressure, water boils at 100 °C, a pipe breach may cause such a space to quickly fill up with scorching hot steam. In order not to impose costly additional safety requirements on the proposed system in Hechengli it seems sensible to recommend a low-temperature grid.

If microturbines such as the one referred to in Section 2.6.2 are used for combined heat and power production, resulting temperatures at the outlet for cooling water will lie around 83 °C. Therefore, maximum supply pipe temperatures of 80 to 85 °C seem to be reasonable. Keeping to temperatures below 85 °C also has further advantages. First, it leaves the choice open between using either conventional steel media pipes, or ones made from linked polyethylene (PEX), which may exhibit undesired creeping at high temperatures. Second, the grid can be installed without the need to consider special fittings at bends and forks, *etc.*, in order to absorb thermal expansion of the pipes. This greatly simplifies installation as well as possible repairs or future connection of new customers (Andersson, 2000-02-09).

When it comes to indicating a lower temperature limit, referring again to Section 2.6.2, the inlet temperature of the microturbine’s cooling water is 50 °C. However, if in future hot tap-water supply is added to the end-user circuits, one has to especially consider additional aspects of comfort-related and sanitary nature. Due to the risk of diseases such as Pontiac fever, or potentially mortal pneumonia, both of which are caused by the bacteria *legionella pneumophila*, German authorities require that hot tap-water temperatures do not fall below 60 °C (Frederiksen and Werner, 1993). However, in some cases a lower mean temperature may be used, if, at regular intervals, the water is heated above 60 °C.

Based on the discussions above, and in order to provide a basis for calculations, grid temperatures of 80 and 60 °C in supply and return pipes were chosen, respectively, indicating a difference of 20 K. These temperatures are quite normal and uncontroversial. Until the early 1980s they were explicitly recommended in Swedish building standards for dimensioning of district-heating systems (Frederiksen and Werner, 1993).

3.5 Pipe dimensions

In technical and commercial contexts the dimension of a district-heating pipe is generally referred to by stating its inner diameter (d). It is important to pay careful attention to the choice of pipe dimensions when planning a grid, since not only are there many physical restraints but dimensions also affect the cost. Smaller pipes are cheaper than larger ones.

In choosing pipe dimensions, the pressure characteristics of the grid are of great importance as a limiting factor. Other parameters that influence the possibility to choose freely are (i) the required thermal power transmission capacity of the pipes, (ii) the ability of customers' heat exchanging equipment to cool the grid water, and (iii) the flow velocity of the medium in the pipes.

3.5.1 Maximum specific pressure drop

The limiting properties of pressure (p) are easily illustrated by a simple diagram of p versus L (the grid distance). Sketching the pressure in both supply and return pipes in the same diagram results in what can be called the pressure cone of a grid. Figure 9 (next page) shows schematically the pressure limitations of the Hechengli grid, such as it is proposed and presented in Figure 7 above, not taking into account, however, the distortions that arise due to topographical altitude variations.

The gradients of the dashed lines in the diagram show the maximum allowable specific pressure drop (Δp_L, $\Delta p_L = |dp/dL|$) of the Hechengli grid, given three additional constraints:

1. Pressure in the supply pipe should not exceed a maximum value. In a grid with direct connection between distribution and end-user circuits, the value is determined by the ability of the equipment of the nearest customer to withstand high pressures.
2. The pressure difference between supply pipe and return pipe at the most distant grid perimeter must be greater than a minimum value. In a direct-connection grid, this value is determined by the resistive properties of the radiator circuit of the most remote customer.
3. Pressure in the grid should not fall below a minimum value. Where the effect on pressure of the topographical profile can be neglected, the lowest value typically occurs at the point where the return pipe returns to the production unit.

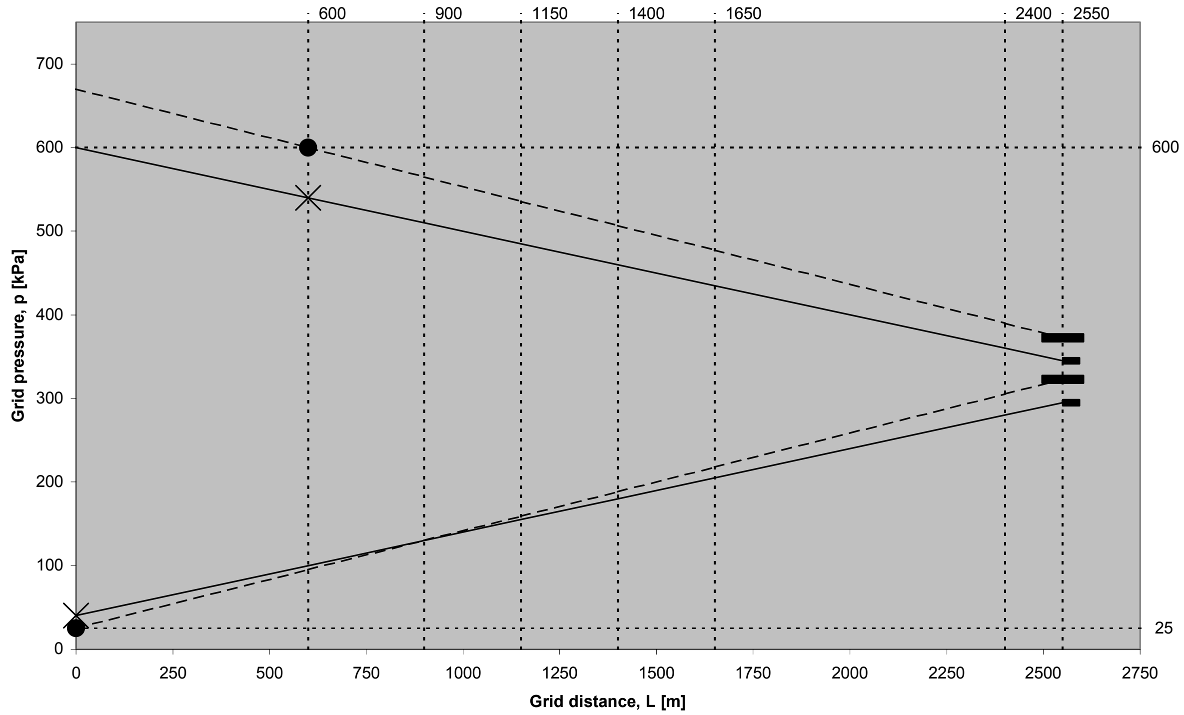

Figure 9. Pressure cones of the proposed Hechengli grid without topographical adjustments: Arithmetical boundary case, $\Delta p_L \leq 0.12$ kPa/m (dashed lines) and possible applied boundary case, $\Delta p_L \leq 0.10$ kPa/m (continuous lines)

For the proposed Hechengli grid, node A (L=600 m) is anticipated as the point where the nearest customer of the grid can be located (having in mind the possible future connection of the poultry and fertiliser plants). In Scandinavia, 1600 kPa is a commonly used maximum pressure for grids in indirect systems (Frederiksen and Werner, 1993). In a direct system, however, grid pressure has to be lower. According to Chinese Standard JCJ30.1-86, approved by the Ministry of Construction, there is a maximum operating pressure of 800 kPa for the radiator type most commonly used in China (He, 2000-02). Therefore, allowing for a safety margin of 30 %, 600 kPa is used as the maximum supply pipe pressure at node A in this report, and the limitation is indicated by a filled circle and a dotted line in the diagram above. The safety margin is applied partly as a general precaution, partly because there are no numerical data on the Hechengli topography. It is known, however, that the location of the plant is elevated above the rest of the grid, meaning that the real pressure in pipes and nodes will exceed, rather than fall below, the values presented here. The lowest pressure allowed, 25 kPa, occurring in the return pipe at node P (L=0 m), is indicated in the same way as the maximum limit. Also from Scandinavian experience, the minimum pressure difference, necessary to uphold circulation in an end-user circuit, is assigned the value 50 kPa (Andersson, 2000-02-09). In Figure 9 this difference is illustrated by parallel bars at the grid perimeter (node B, L=2550 m). In order to increase the pressure from its lowest value a pump is needed, but no further attention will be paid to this issue in the current report. In large grids it may even be necessary to have pumps at several locations along the grid to prevent the pressure from dropping too much. This ought not to be necessary in small grids such as Hechengli's.

The specific pressure drop occurs naturally due to the resistive properties of pipes, medium, and flow. It can be explained and calculated using fluid mechanical relations. For straight pipes the expression can be written (Frederiksen and Werner, 1993):

$$\Delta p_L = \frac{1}{2}\Lambda \rho v^2/d \quad (22)$$

Δp_L = specific pressure drop	[Pa/m]
Λ = friction coefficient of the pipe	[—]
ρ = density of the grid medium	[kg/m^3]
v = flow velocity of the medium	[m/s]
d = inner diameter of the pipe	[m]

If the pressure drop exceeds the value indicated by the gradient in the diagram of Figure 9, the pressure will not be high enough to stable heat delivery at the perimeter of the grid. Assuming that the specific pressure drop is constant across the entire grid*, the prerequisites above, together with some straightforward arithmetic, yield a maximum specific pressure drop in Hechengli of 0.12 kPa/m.

In practical engineering, a commonly stipulated maximum specific pressure drop is 0.10 kPa/m (Løgstør Rør, 1997). Applying this value, the continuous lines in the diagram show a possible limiting pressure profile, which meets the specified constraints.

3.5.2 Thermal power transmission capacity

As illustrated below by Equation 23, the thermal power that can be transmitted by a pipe is dependent on the flow of the medium through it. The importance of the pipe diameter for the magnitude of the flow is clearly shown by Equation 24:

$$P = \rho c \Phi \cdot (T_s - T_r) \quad (23)$$

$$\Phi = \frac{1}{4}\pi d^2 v \quad (24)$$

c = heat capacity of the grid medium	[J/kgK]
Φ = flow of the grid medium	[m^3/s]

In an optimally dimensioned grid, the diameter of the pipe will change at every node, since each new branch carries only a share of the total power delivered to the node. In practice, the freedom to choose pipe dimensions is limited, for example by the product range provided by the pipe manufacturers. In the proposed Hechengli grid, pipes have been divided into four categories: feed branch, main branch, and side and service branches (refer to Figure 7). Since the main branch and side branches each fork at many nodes, in theory this might motivate frequent changes in pipe dimensions. However, because exact distances between nodes are not known, there is little point in making any detailed calculations at this stage. Instead, side branches, which are fairly short (less than 150 m), are modelled as being uniform in diameter, as are the feed and service branches. The modelled main branch, which is considerably longer (2 km), is divided into five segments of uniform dimension. The pipe diameter changes at the nodes labelled with the Roman numerals I to IV in Figure 7.

* This assumption, although not altogether correct, is a commonly made generalisation in district-heating engineering. In reality, the specific pressure drop varies within a grid depending on the diameter and inner surface structure of the pipes. Ageing processes in a pipe, like corrosion and deposition, increase its resistive properties (Λ). Moreover, variations in the topographic profile of a grid distort the pressure cones. It is important to consider this effect in practical engineering (Frederiksen and Werner, 1993).

Assuming a static heat loss of 30 % from all types of pipe, and a maximum of seven service nodes in every side branch, the required minimum thermal power transmission capacity of each pipe category and segment can be calculated. The results presented in Table 12 are based on a dimensioning thermal power demand of 8.1 kW per household (as given by solar-corrected P(T) modelling), implying that the grid in future is expected to be able to carry peak-load demand.

Table 12. Minimum required thermal power transmission capacity of the pipe segments of the proposed district-heating grid in Hechengli

Pipe segment	Feed branch	Main branch					Side branch	Service branch
		I–II	I–III	II–IV	III–V	IV–VI		
Required thermal power transmission capacity [MW]	>2.6	>2.2	>1.0	>1.6	>0.41	>0.81	>0.081	>0.012

3.5.3 Heat exchanging ability of end-user equipment

Apart from flow, the ability of radiators in the homes of the customers to transfer heat from the grid medium to ambient space also greatly influences the magnitude of the thermal power transmitted by the grid. The more the grid water is cooled, the more power is delivered, which is clearly illustrated by Equation 23, above. Of course, the temperature difference between the supply and return ends of an end-user circuit may vary with time, and it also depends on the absolute temperature levels of the grid. In engineering crib sheets supplied by a Scandinavian pipe manufacturer, grid water temperature differences vary from 20 K to 50 K (Løgstør Rør, 1997). Thus, the value used in this report for calculations on the Hechengli grid, 20 K, is not unreasonable, although it is not very high.

3.5.4 Flow velocity and pipe dimensions

From several previous equations (22, 23, and 24) it can be seen that the flow velocity of the pipe medium is an important parameter, which is coupled to pipe dimension. In fact, the magnitude of flow velocity may itself impose restrictions on the choice of diameter. Too high velocities increase the risk of erosion and pressure shocks (Frederiksen and Werner, 1993). Bearing this in mind, a diagram of diameter versus flow velocity may be used to illustrate how the choice of dimension is influenced by all the different constraints that have been mentioned. Figure 10 (next page) shows such a diagram.

There are two sets of curves in the diagram, corresponding to Equations 22 and 24. Emanating from the origin are parabolas, showing the constant specific pressure drop (Δp_l).[*] The hyperbolas with values decreasing from infinity show the correlation at constant power-transmission capacity (P) and constant supply–return pipe temperature difference (T_s–T_r).

[*] *NB*: The parabolas in the diagram are based on Equation 22, assuming that the friction coefficient of the pipes (Λ) remains constant. In reality, however, the value of Λ is dependent on the pipe diameter (d), increasing non-linearly as the diameter decreases (Løgstør Rør, 1997). Still, when establishing approximate dimensions only, assuming constant Λ may be convenient. If greater mathematical accuracy is sought, iteration can provide sufficiently precise results, even if the exact expression relating Λ to d is not known.

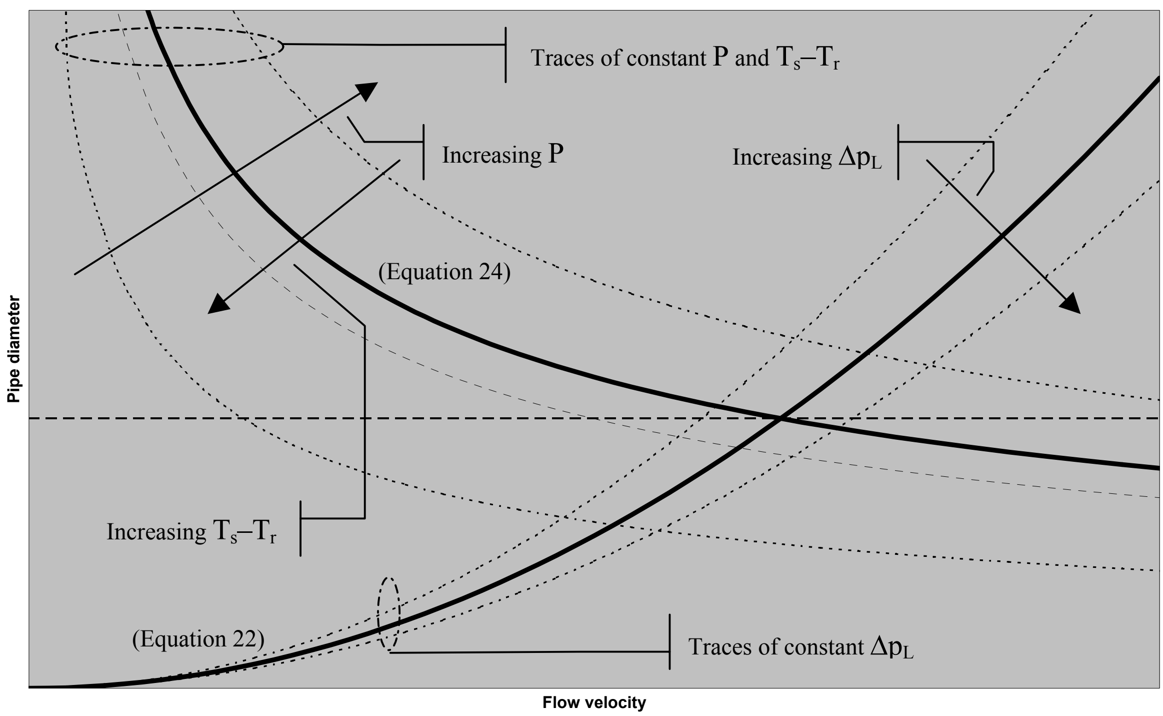

Figure 10. Diagram of pipe diameter versus flow velocity indicating the outlines of physical constraints in a distribution grid for district heating

The way in which the optimal pipe dimensions are determined in a diagram like this can be described as follows:

1. Note the outlines of the physical constraints represented by maximum specific pressure drop (a parabola) and flow velocity (a vertical line). The area below and to the right of these lines is, so to speak, "out of bounds."
2. Determine the dimensioning power transmission capacity of the grid segment in question, and estimate the smallest temperature difference likely to occur between supply pipe and return pipe. These values correspond to the maximum load that may be carried by the segment. Identify the hyperbola representing this load.
3. Trace the outline of the hyperbola until it intersects either of the other two constraints.
4. On the vertical axis, read the magnitude of the resulting pipe diameter. Choosing pipes with a smaller diameter will make the segment under-dimensioned, since at dimensioning load, either the specific pressure drop or the flow velocity, or both, will exceed the permissible values. Choosing larger pipes, on the other hand, makes the segment over-dimensioned.

Table 13 (next page) displays the results obtained when applying this method to determine the co-ordinates of the intersection points for each of the different pipe segments of the proposed grid in Hechengli. Constants and variables have been assigned the following values. Δp_L=0.10 kPa; P varies according to the values in Table 12; (T_s–T_r)=20 K; Λ=0.024, which is the average value for the pipes presented by Løgstør Rør in its crib sheet (Løgstør Rør, 1997); and the physical properties of water are taken to be c=4180 J/kgK and ρ=1000 kg/m^3 (Ekbom, 1986).

Table 13. Calculated intersection co-ordinates in a diagram of diameter versus velocity for the pipe segments of the proposed district-heating grid in Hechengli at dimensioning thermal power demand and maximum specific pressure drop

Pipe segment	Feed branch	Main branch					Side branch	Service branch
		I–II	I–III	II–IV	III–V	IV–VI		
Flow velocity (v) [m/s]	1.22	1.18	1.01	1.11	0.84	0.97	0.61	0.41
Pipe diameter (d) [mm]	180	168	122	149	86	113	45	21

3.6 Supply stability

Based on the assumption of the future existence of base-load heat supply from electric-power generation, this report proposes the initiation of a phased expansion of a district-heating grid in Hechengli. This strategy leaves the door open for a system ultimately covering the entire village. Depending on how the trigeneration plant's capacity to produce electricity develops in the future, its share in meeting the total heat load will probably be greater in the initial phases than subsequently. At the time that this report was written, the magnitude of the need for supplementary thermal power capacity could not be predicted, since the type and final capacity of the base-load supply facility had yet to be determined by the project management. Nevertheless, reference to Table 11 (in Section 2.6.2) may serve as a guide.

However, there is much more to the issue of supply than just matching capacity with expected load. An issue of great importance when designing communal commodity-supply systems is the stability aspect. For example, it is necessary in district-heating systems to supplement the steady-state base-load supply facility with stand-by equipment which, if need be, can carry the entire required load. In the event of malfunction there must be technical resources to sufficiently limit both the inconvenience of customers and the cost of emergency measures. It is evident, also, that if all supply capacity is concentrated to one location, the system becomes more vulnerable than if the capacity is spread out across the grid.

3.6.1 Auxiliary thermal power supply

The most obvious way in which to achieve supply stability is to install auxiliary thermal power supply units. These may be connected either centrally at the supply end (although not necessarily in the same location as the base-load unit), or peripherally at each of the end-user circuits. Central and peripheral auxiliary supply may also be used, of course, as complements to each other.

When dimensioning the pipes of the Hechengli grid in this report (referring to Tables 12 and 13), it has been postulated that the grid will be able to carry the entire peak-load demand (corresponding to 8.1 kW per household*). Also, it is implied that all power be fed into the main branch at node I (see Figure 7). The significance of these facts is that the grid is dimensioned to manage operation completely with central power input, which is concentrated at the plant site or along the feed branch. If these assumptions are altered, the figures related to pipe dimensions must also be. For example, it may be argued that in order to decrease vulnerability, a central auxiliary power supply unit should be located at one of the end nodes of the grid. This strategy would change the required thermal power transmission capacities of the main branch segments, such as they are proposed in Table 12. If, on the other hand, there is no ambition for the external grid to be able to carry the whole dimensioning load, the required transmission capacity will, of course, decrease for all pipe categories. Such a solution, although it reduces the initial investment cost for pipes, also makes the system dependent on the existence of a peripheral auxiliary thermal

* At DOT=–23 °C, solar-corrected P(T) modelling (not including possible future heat demand due to grid-based supply of hot tap-water).

power supply. This may limit the potential benefits offered by a central supply, such as the increased comfort level of the residents, and an overall improved environmental performance resulting from diminished individual household use of gas, coal or other fuels.

Today, the households of Hechengli individually supply themselves with all the thermal power that they require. Provided that a prospective district-heating grid is constructed in such a way as not to remove the households' ability to do so in the future, this means that there will be a comprehensive peripheral auxiliary thermal power supply-capacity in the Hechengli grid. Therefore, from a stability point of view it will be a very robust grid.

3.6.2 Heat accumulator tanks

Another way in which to enhance supply stability is to employ controlled heat accumulation. By storing hot water in accumulator tanks, intermittent load peaks and transient disruptions in base-load supply can be managed, delaying or even avoiding the need to resort to auxiliary power supplies with high operating costs. In applications of combined heat and power production, heat-supply variations may arise not only from malfunctions, but also from the need to adjust the proportion of electric output in order to meet the instantaneous power demand. Since the plant in Hechengli is planned primarily for electricity generation, installing some kind of heat accumulation equipment would be a wise strategy, in order to increase the freedom of action in a possible district-heating system. Also, if a leak causes the grid to lose water, an accumulator tank offers a reservoir of good-quality water, which may allow the system to keep running temporarily while proper measures are being implemented to locate and repair the damage.

As always, there are losses associated with the storage of heat, but these can be sufficiently reduced by suitable insulation of the accumulator tanks. Functionally, an accumulator can consist of a single tank or of several separate tanks in series. The system may be either pressurised or non-pressurised, which greatly affects the cost. In general, pressurised accumulator tanks cost about 3 to 4 times more than non-pressurised ones (Andersson, 2000-02-09). More detailed discussions on accumulator design, technology and performance can be found in other literature, in which the subject is treated in more depth (Frederiksen and Werner, 1993).

When dimensioning an accumulator, the key question is the required capacity, given the aspired level of supply stability and taking into account the nature and cost of the auxiliary power supply. The storage capacity of an accumulator is simply a linear function of its volume, making calculations simple enough:

$$Q=\rho c(T_{store}-T_r)V \qquad (25)$$

Q = thermal energy storage capacity [J]
T_{store} = temperature of storage medium [°C]
V = accumulator volume [m^3]

4. Economic implications

4.1 Present perspective on economy and trigeneration

This study does not claim to perform more than a preliminary evaluation of a proposed district-heating grid in Hechengli. Many parameters of technical significance are uncertain and others depend on strategic choices, which need to be addressed and determined in by the local authorities and the management of the Hechengli bioenergy project. Therefore, there is little use in making detailed calculations on the economic implications of district heating at this stage. The following sections are intended to take up a few economic aspects only, which may be of interest as references when deciding upon how to proceed in developing the trigeneration concept.

4.2 Cost

Direct monetary investments in equipment and labour are the main economic components considered in the evaluation of the profitability of a project. Therefore, such aspects will be briefly commented upon for the case of prospective trigenerated district heating in Hechengli.

4.2.1 Pipes and radiators

Below, Table 14 serves to give a rough idea of the magnitude of the investment cost for the district-heating pipes required to establish the Hechengli grid. Pipe dimensions have been selected in accordance with the phased expansion approach, meaning that although costs are presented for three different grid sizes, dimensions are unaffected as they are intended to ultimately carry the heat load of the entire village. Of course, the prices of pipes given in the table are only approximate. Quoted from a price list by the Chinese pipe manufacturer HotNet (formerly a joint venture company with ABB China), they exclude value-added tax (1.17 % surcharge) and were valid for the Beijing area until 1999-12-31 (Yang, 1999-11).

Table 14. Pipe lengths and estimated investment costs for pipes in the proposed Hechengli grid, given three different grid sizes in the first stage of a phased expansion approach to establishing district heating in Hechengli. Diameters and prices of pipes as suggested in a price list for Beijing by the Chinese pipe manufacturer HotNet (Yang, 1999-11)

Grid size	Pipe segment	Feed branch	Main branch					Side branch	Service branch	Total grid
			I–II	I–III	II–IV	III–V	IV–VI			
84 hh	Pipe length (double grid distance) [m]	1800	500	500	—	—	—	3000	2016	7816
112 hh		1800	500	500	—	500	—	4000	2688	9988
224 hh		1800	500	500	1000	500	1500	8000	5376	19176
	Diameter (*) [mm]	219 (180)	219 (168)	159 (122)	159 (149)	89 (86)	114 (113)	57 (45)	57 (21)	
	Price [CNY/m]	387	387	240	240	128	164	98	98	
84 hh	Cost [thousands CNY]	696.6	193.5	120.0	—	—	—	294.0	197.6	1501.7
112 hh		696.6	193.5	120.0	—	64.0	—	392.0	263.4	1729.5
224 hh		696.6	193.5	120.0	240.0	64.0	246.0	784.0	526.8	2870.9

* Figures within parentheses present minimum pipe diameters according to previously calculated estimates (refer to Table 13).

Assuming that the first phase of constructing a district-heating grid in Hechengli encompasses either 84, 112, or 224 households, the table indicates pipe investment costs amounting to 1.5, 1.7, or 2.9 million CNY, respectively. These figures can probably be regarded as maximum estimates, since, according to the manufacturer, lower prices may be offered to rural buyers (Yang, 1999-11). Also, the price list supplied by HotNet for this study does not present an exhaustive picture of the range of pipes available. Naturally, there are other, competing manufacturers of district-heating pipes in China, and prices will be subject to negotiation. Furthermore, and with respect to over-dimensioning, there is reason to believe that pipes corresponding better to actual needs can be selected, once detailed dimensioning has been carried out for the real village, and not just for the grid proposed in this report. The order of magnitude of cost presented here, however, ought to be representative.

Not only pipes for distance distribution are needed in a district-heating system. It is also a requirement that all connected households be equipped with hot-water radiators and pipes. Generally, it is not all that common for rural Chinese households to use this type of technology for space heating. In Hechengli, however, which is a village with a comparatively high standard of living, as many as 50 % of households already have radiators, similar to Mr Hua Jisheng and his family (Li, 1999-11-08). For the purpose of cost estimation, these households are assumed to be spread out uniformly throughout the village. This means that no matter what portion of Hechengli is included in the first phase of the establishment of a local district-heating grid, only half of the homes need to be fitted with hot-water pipes and radiators. According to Professor Liu Guoxi at the University of Agriculture in Jilin, the cost of such an installation can be estimated to be 1000 CNY per household (Liu, 1999-11-07).

4.2.2 Heat supply

Base-load thermal power for a district-heating grid in Hechengli would be supplied by the proposed bioenergy plant, the primary purpose of which is the production of gas and electricity. In the following calculations it is assumed that unless the heat is used for residential district heating, it will be treated as waste and discarded. Therefore, in the economic considerations of this report base-load heat is not associated with any cost.

The required magnitude of peak-load and auxiliary power capacity depends not only on the size of the trigeneration plant, but also on whether a direct approach or an expansion strategy is chosen for the installation of the district-heating system. However, it is clear that the existing capacity of peripheral supply is large enough to carry the entire demand at all times, although the equipment may have to be upgraded in many cases. Installing central supply facilities to complement the peripheral ones would have the advantage of increasing residents' comfort, and decreasing environmental stress caused by combustion in individual households, but an economic evaluation of such components is complicated. This is one reason why they are seldom internalised in investment calculations. Although important, there is no room in this report for a deeper development of this discussion. Instead, and because of the difficulties at the current phase of the project's implementation in dimensioning the actual need for supplementary capacity and estimating the associated costs for central auxiliary supply, cost calculations presented here will not include any central auxiliary heat installations at all. As is already noted, the system is not dependent on such investments in order to be functional. Any investments in upgraded peripheral power supply technology (*e.g.* replacing coal burners with gas-fuelled ones) are considered necessary, regardless of whether district heating is established or not, and the costs are not attributed to the possible installation of district heating.

Like central auxiliary heat-supply, a heat-accumulation facility is not necessary for the operation of a district-heating system in Hechengli. Nevertheless, it is an important feature for a district-heating grid. Seeing that there is a range of different technical solutions to choose from, but also that an attempt at finding out which options are applicable in Hechengli would require a general survey of the Chinese suppliers market, this topic is left for subsequent studies to fully explore. However, an example of how an accumulator may be dimensioned is presented below.

According to Equation 25, and assuming a temperature difference of 20 K between storage and return pipe media, an accumulator volume of 3400 m^3 equals a capacity close to 80 MWh. Based on an average power demand in the heating season of 4.8 kW per household (as estimated in the solar-corrected P(T) model), and allowing for a loss quotient of 30 % in distribution, this amount of energy would suffice to support the whole of Hechengli for more than two days. This is quite a long period of time, even though the accumulator volume is in no way extraordinary. In comparison, large district-heating grids may well have single tanks that contain several tens of thousands of cubic metres (Frederiksen and Werner, 1993). If the temperature difference were allowed to increase, the indicated capacity would increase correspondingly. There is no theoretical reason for the storage temperature to match the maximum supply pipe temperature, but if the temperature of the water exceeds 100 °C the accumulator must be pressurised, which imposes extra costs on the investment.

In order to at least provide a foundation for economic estimates, the following information may be considered. In November 1999, the corporate group Midroc Scandinavia in Sweden offered delivery and construction of a 3400 m^3 non-pressurised, hot-water stratification accumulator for the price of 3.5 million SEK (roughly the same in CNY[*]) (Wallin, 2000-05-04). Transferring this cost to Chinese conditions in Jilin is difficult. Paul Henderick refers to a study by Fuqiang Yang from 1995, where the cost of a new integrated combined cycle power plant in the United States is compared to that of an equivalent one in China. According to this study, the average cost reduction achieved by making maximal use of Chinese manufacturing of related technology exceeds 50 % (Henderick, 2000). Being aware that the estimate fails to take into consideration several issues of importance, such as the difference in type of technology and the differences in cost between the United States and Sweden *etc.*, it will be assumed that 1.7 million CNY is a feasible investment cost in Jilin for an accumulator equivalent to the one described above.

4.2.3 Construction and operation

For simplicity, no specified investment costs for on-site structural construction will be included in this economic review of the establishment of district heating in Hechengli. Naturally, this is not a true representation. However, irrespective of the district-heating system, the gasification plant will still be built, including both an electricity-generating facility and an underground pipe grid for gas distribution to the village households. Therefore, a major part of the labour cost of installing both the base-load supply units and the pipe grid will arise anyway and may be allocated to the project's core products: gas and electricity. The additional labour costs due to the installation of extra equipment (such as three parallel pipes instead of a single one) are neglected. Subsequent studies will have to establish the true relations and suggest a policy for the sharing of costs. The same argument is used regarding the issue of land acquisition. The investment costs already stated for other equipment than base-load heat supply and distribution pipes, *i.e.* household radiators and the accumulator tank, are considered to include labour for on-site installation.

The cost of operation of Hechengli's district-heating system will include posts such as:

- fuel for peak-load and auxiliary heat supply,
- water for the grid,
- electric power for pumps *etc.*,
- wages for workers,
- management, and
- maintenance.

[*] On 30 December 1999 1 CNY equalled 1.05 SEK (Teledata, 1999-12-30).

These aspects have not been incorporated into this study, which is why no quantitative estimates are made. Instead they are left for future investigations.

4.2.4 Annual cost of equipment and construction

According to Professor Mao Yushi, formerly of the Unirule Institute of Economics in Beijing, assuming an annual interest rate of 4 % is reasonable for environmental projects in China (Mao, 1999-11-24). Based on an economic service life of 10 or 20 years, and under the premises described above, estimates may be made of the annual cost of equipment and construction of the first phase of establishing district heating in Hechengli. For the purpose of enabling comparisons, cost calculations have been performed for three different grids. The first one, which does not include an accumulator, covers 84 households. The other two, covering 112 and 224 households, both include a 3400 m^3 accumulator.

In order to transform the initial investment into annual costs, the annuity method has been applied. Annuities are calculated by multiplication of the investment by the so-called annuity factor (f_a), which can be defined as follows (Ekbom, 1986):

$$f_a = r\,(1-(1+r)^{-n})^{-1} \quad (26)$$

- f_a = annuity factor [—]
- r = interest rate [—]
- n = economic service life [years]

Table 15 presents the financial costs to be borne by the district-heating grid if it were a conventional project, where customers (*i.e.* the end-users) have to bear the entire investment. From this perspective, two things are especially important when considering the figures. First, costs arising from operation and working capital are not included. Second, the results only include distribution of whatever base-load heat the trigeneration plant can supply. This amount, in turn, depends on the technology chosen for electrical generation; its type and capacity. The cost of fuel for peak-load heat, which may constitute a considerable part of the total load, especially as the grid size increases, must be added.

Table 15. Estimated investment costs and corresponding annuities for three different-sized district-heating grids

			Grid size	Distribution pipes	Radiators	Accumulator	Total grid	per hh
Investment cost [thousands CNY]			*84 hh*	1502	42	—	1544	18.4
			112 hh	1730	56	1700	3486	31.1
			224 hh	2871	112	1700	4683	20.9
Annuity [thousands CNY]	Interest rate: r=0.04	Service life: n=10 years (f_a=0.1233)	*84 hh*	185.2	5.2	—	190.4	2.3
			112 hh	213.3	6.9	209.6	429.8	3.8
			224 hh	354.0	13.8	209.6	577.4	2.6
		Service life: n=20 years (f_a=0.0736)	*84 hh*	110.5	3.1	—	113.6	1.4
			112 hh	127.3	4.1	125.1	256.5	2.3
			224 hh	211.2	8.2	125.1	344.6	1.5

Assuming that the electrical generator to be installed in Hechengli can be represented by a single 75 kW_e turbine, such as the one previously discussed in Section 2.6.2, a modest estimate based on Table 11 suggests that at least 20 % of the average wintertime heat demand of 84 households can be met. Returning to the household of Mr Hua Jisheng for comparison, their current usage of coal amounts to 5 tonnes per year, of which roughly 60 %, or 3 tonnes, are estimated as being used for residence space heating (refer to Appendix A). As observed in Changchun in November 1999, the market price for household coal was 250 CNY per tonne. Thus, if for argument's sake a district-heating system could match the entire space-heat demand, this would correspond to a reduction of approximately 750 CNY in the annual expenditure for coal of Mr Hua's household. Compared to the grid's annuity cost of 1400 CNY per household (as suggested by Table 15, given a service life of 20 years), it is clear that in a conventional financial context, district heating in Hechengli cannot be competitive on its own. Therefore, profitability and competitiveness have to be assessed more comprehensively to include other benefits for residents and society in order to motivate an investment in district heating.

4.3 External costs and savings

In an attempt to balance the economic perspective of this type of project, one may consider other aspects than the purely financial ones, which often tend to exclude several points of significance to the situation as a whole. While not attempting to make explicit calculations, this report presents a few perspectives worth considering when identifying external costs and savings.

4.3.1 Environmental perspectives

In the agricultural areas of northern China, vast amounts of harvest residue are produced every year. Although much is made use of as fuel, fodder, fertiliser, or raw material for handicraft and industrial processes, large amounts still remain that have to be disposed of. Traditionally, this material is simply burned in the fields, which is not only a waste of a potentially valuable resource (Liu, 1999), but because of smoke and particulate emission it is also a threat to the local environment. Some of the environmental impacts are relatively easy to assess, even economically. In 1997 at Shijiazhuang Airport in Hebei Province, for example, the smoke from burning in the fields caused several delayed flights and forced landings, which were estimated to have inflicted direct costs amounting to almost one million CNY. Similar events also occur in other provinces. Moreover, along highways and railways smoke causes traffic disruptions such as standstills or serious accidents, and in the countryside local residents suffer from smoke-induced problems in their eyes and lungs (Chen, 1999). Finding efficient ways of using the residue as a resource would result in costs savings, which might be substantial. The biomass gasification programme in Jilin is an important initiative in such an effort. Within this framework, trigeneration and, more specifically, district heating could be used as a means to achieve increased efficiency in resource management.

Jilin's gasification programme not only promotes better air quality on the local scale. Also from a global perspective it represents a contribution to the efforts of reducing environmental damage caused by atmospheric pollution. Modern China is almost exclusively dependent on fossil energy, which accounts for nearly all of its primary energy production, exceeding 1100 Mtce per year in 1994. Coal is the dominant source of energy, alone accounting for more than 70 % of total energy production (Sinton, 1996). The emission of carbon dioxide from the burning of fossil fuels contribute to global warming due to the so-called greenhouse effect, which is a problem recognised by the nations of the world in the United Nations Framework Convention on Climate Change. By introducing non-fossil, yet modern and high-standard alternatives onto the energy market of rural China, it may be possible to prevent coal from becoming increasingly important and dominant also as a small-scale household fuel. As the rural standard of living increases, more and more residents abandon the use of conventional low-tech biomass stoves, looking for more comfortable ways of satisfying their energy demand. In arguing that trigeneration is an effective way to use biomass as a modern renewable energy resource in Jilin, it follows that district heating, as it is proposed for Hechengli in this report, would increase the potentially exploitable amount of non-fossil energy. Therefore, part of the value of climate-change mitigation may be credited to such a project.

4.3.2 Health-related perspectives

An important area, to which much international research is specifically devoted, concerns health effects resulting from indoor combustion. Burning of wood or other unrefined biomass in individual households is still widespread for cooking, heating and lighting across the world, especially in rural areas of developing countries. Because of incomplete combustion, which often occurs due to the non-ideal burning conditions in a home, particulate and gaseous emission may be a potential health hazard to the residents. On a large scale this can constitute a substantial economic burden to society, since poor health in the population will inflict indirect costs due to loss of labour and an increased need for health care (UNDP, 1997).

In agricultural parts of China such as rural Jilin, using unprocessed agricultural residue as a burning fuel directly in the homes is standard practise. Effective combustion of such fuel requires conditions that are impossible to achieve in manually fed, low-technology stoves of the type normally used. Therefore, soot and other air pollutants are a common problem. In the village of Shijiapu, a few dozen households have been able to benefit from the local gasification plant through connection to the gas grid. In the household of Mr Niu Yulin, his family has noted a substantial improvement in indoor air quality after they changed from using stalk and cobs from maize as fuel for their stove. Now that they use gas instead, the previously heavy accumulation of dust and soot in their home has more or less disappeared (Niu, 1999-11-05). The combustion of gaseous fuel is much easier to control than that of solid fuels, and the particulate emissions are substantially reduced. However, because of possible gaseous pollutants the health risk may still be serious. Especially when using gas of the kind produced in Shijiapu (and in future also in Hechengli) there is cause for caution, knowing, for example, that the gas includes high amounts of carbon monoxide (JPERI, 1998), which is highly toxic.

Indications that indoor air quality is indeed a health problem in rural China can be found in national statistics. According to figures from 1997, respiratory disease was the fourth most common cause of death among China's urban population, accounting for 14 % of the total mortality. Only malignant tumours, cerebrovascular disease and heart disorders reaped more victims. In rural areas, however, respiratory disease was the single most deadly malady, responsible for more than 23 % of all deaths. Among women, who generally spend more time indoors than men do, as much as 25 % of deaths was due to respiratory disease (CSY, 1998). Of course, no really conclusive statements can be made from these figures, although they do support rather than contradict a connection between inefficient indoor combustion and poor health among the population of China. The economic consequences, which cannot be estimated in this report, may be considerable.

By installing central heating, the need for combustion in individual households can be reduced, or restricted to cooking. Although the installation of a rural district-heating grid in Hechengli would do little to change national health statistics, it may be a powerful way for the leadership to demonstrate their recognition of the need to improve indoor air quality in rural homes, promoting general good health and improved standards of living.

4.4. The contextual perspective

Not only factors of technical and economic nature should be allowed to influence the decision of whether or not to go through with an infrastructural investment of the kind discussed in this report. All projects have to be realised in a context, which must be taken into consideration and understood if proposals are to be correctly assessed. Otherwise, there is a potentially significant risk that unforeseen obstacles or other problems will render assumedly basic conditions invalid. Especially when projects involve international expertise, relevant contextual knowledge must be carefully highlighted and should not be dismissed as being implicitly taken into consideration, although this might be true when projects are limited to domestic evaluation.

4.4.1 Culture and social patterns

Throughout northern China, a kang is the traditional method of supplying space heat in rural homes. Even in comparatively well-to-do homes, such as Mr Hua's in Hechengli, where modern hot-water radiators are used to achieve better efficiency and quality in the internal heat supply, the kang still plays an important role as the social centre of the home, and the place where many day-time activities take place. In the cultural context of rural northern China, the kang's role in everyday life is of obvious significance. This must not be overlooked when considering a change in heat-supply technology. By installing district heating, household burning of fuels in the kitchen stove will only be necessary for cooking, thus being limited to a few hours a day. As a consequence, the kang would be left unheated. Investigating whether or not residents would perceive such a change as negative is essential, in order not to risk a failure of a district-heating investment due to public lack of interest or even resistance. Such problems might be avoided by installing hot-water radiators in the old kang.

Another social aspect of significance to a district-heating grid in Hechengli is the fact that traditionally, there is no regular demand for heat outside the heating season. How this may change or influence people's perception of the new technology, and how it may influence the equipment itself, are also issues which should be assessed.

4.4.2 Policy

Local policies of different kinds exist as consequences of local conditions, and they will inevitably influence the operation of a trigeneration plant in Hechengli. Although important, it is not the purpose of this study to specifically identify such aspects. For example, however, it may be clarifying to briefly discuss the prospective ambition to find a market outlet on the public electric grid for locally produced small-scale electricity. This idea is expressly suggested in, for example, Paul Henderick's report on the Hechengli project, where it is suggested that it may be possible to sell excess electric power from the village plant on a future market (Henderick, 2000). Making recommendations or decisions about what capacity to install under such premises may prove unwise when taking into consideration the actual local context, which is dependent on policy and the opinion of Chinese grid-owners.

Under present circumstances, efforts to sell small amounts of electricity to the public grid will probably be in vain, since the currently installed over-capacity of large-scale coal-fired power in northern China makes grid-owners hesitant to accept small-scale alternative power on the grid. Only if they are exposed to more or less compelling incentives from a political or regulatory body, for example through the introduction of a minimum required renewable energy portfolio, is it conceivable that the Hechengli plant can actually sell electricity to the public grid. Thus, according to the view of several Chinese experts, connecting prospective electric generators in Hechengli to the grid seems to involve only extra investment costs (*e.g.* new transformation stations) and few, if any, advantages. Instead, the reasonable solution, as it is seen in Jilin, is to employ directly connected electric cables between the plant and its customers, whether they be local industries or private households, rather than involving the public grid (Liu, 1999-11-07).

4.4.3 Alternative solutions for Hechengli

From the perspective of efficient resource use, trigeneration is a conceptually attractive solution for the utilisation of waste heat from electricity production in Hechengli. As a means of also improving the comfort and living standard of residents, district heating is arguably an interesting option, although other priorities may hinder the implementation of such an initiative. Without abandoning the concept of trigeneration, however, there are other possible solutions.

Focusing on industrial district heating, instead of on providing heat to residents, may be an alternative worthwhile investigating. Apart from the existing poultry and fertiliser plants, there are other enterprises, which could come into question. For example, there are plans to construct a village school, which might benefit from central heating. Another solution, pointed out by representatives of local authories, is to use the heat in a nursery for seedlings. In Hechengli many residents grow vegetables in private greenhouses, which means that there may well be a demand for seedlings grown under more controlled and professional conditions than those which farmers might manage by themselves (Li, 1999-11-08). Depending on the nature of such alternative heat customers, for example size and annual duration of demand, distance to the trigeneration plant, *etc.*, the concepts must be further assessed in order to enable more comparisons to be made.

Another possible alternative for the biomass project in Hechengli would be to simply abandon the concept of trigeneration. Assuming that household gas for cooking is the product that in fact has the highest priority, there are basically two strategies to choose from. First, the plant can be designed for gas and electricity only. In this way, gas can be used to satisfy household demand for space heat as well as for cooking, still replacing fossil fuel or low-tech burning of biomass with a more convenient and renewable energy carrier. A large part of the resource used to produce electricity, however, will be wasted in the form of heat. The second strategy would be to concentrate on the production of gas and central heat, in which case waste would be reduced, and an improvement in the comfort and living conditions of residents can be prioritised.

5. Conclusions

A significant conclusion of this report is the suggestion that the energy need for wintertime space heating in a rural household in Jilin may well be twice or three times that currently assumed by many local experts. No previous studies are known to have methodically estimated the actual heat usage or demand, attempting to separate the energy needed for space heating from the energy used for cooking and water heating. The findings of this study imply that while the probable range of current usage is 13 to 17 MWh_{th} per year, calculations indicate that values near or even exceeding 20 MWh_{th} might not be exaggerated. If central heating is conveniently supplied at an affordable rate, household usage may rise compared to present levels. On the other hand, however, measures such as adding insulation in order to reduce heat transfer through the building envelope may contribute to considerable reductions in the space-heat demand of an ordinary rural household.

Because household heat demand seems to be substantially higher than expected, it is doubtful whether the presently planned bioenergy plant in Hechengli will have sufficient capacity to supply the entire thermal power needed to heat the homes of the village. Provided that there is still an ambition to develop the concept of district heating from trigeneration, the project management may want to consider alternative approaches to an extensive direct installation of a residential district-heating grid. In this report, phased expansion is deemed to be a preferable choice compared to a direct approach covering only parts of the village. The main reason is that by dimensioning for an extended system, future freedom of action is less restricted. Estimates suggest that by installing a small grid (without an accumulator tank), initially covering only 38 % of Hechengli's households, direct investment costs for distribution pipes and household radiators might not exceed 1.6 million CNY. This figure can be compared with the investment of nearly 4.7 million CNY required for an extensive grid, which includes an accumulator tank and covers the entire village. However, when considering instead the specific cost per household, the two alternatives do not differ very much. Distributing the investment over 20 years at an interest rate of 4 %, the small grid represents an annual cost of 1400 CNY per household, and the extensive one is only slightly more costly at 1500 CNY.

In a rural Chinese context, the figures discussed above are too high for such investments to be financially competitive. Therefore, this study shows that in a conventional assessment, district heating is not a profitable way in which to use the waste heat from electric generation at the proposed gasification plant in Hechengli. There may still be alternative solutions for a profitable use of the heat, but evaluations of these have not been performed in this study. It is also possible, of course, to abandon the trigeneration concept entirely. However, by including different kinds of external cost in the economic evaluation of trigeneration, residential district heating may still turn out to be a solution worth considering.

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Appendices

Appendix A: Calculations on Mr Hua Jisheng's usage of thermal energy, divided between the residence and the combined rabbitry and pigeonry

To separate Mr Hua's household's usage of thermal energy for residential space heating from the energy used to heat the rabbitry and pigeonry, the P(T) model for demand estimates has been used.

The following data, in Table A:1, describe the modelled space.

Table A:1. Envelope elements of the modelled combined rabbitry and pigeonry (Hua, 1999-11-08)

	[m]	Area [m^2]
Height	2.8	n/a
Façade	4.5	12.6
Gable	6.0	16.8

	Width [m]	Height [m]	Area [m^2]
Window 1	1.0	1.35	1.35
Window 2	1.0	1.25	1.25
Window 3	1.5	0.35	0.53
Door	0.85	2.0	1.7

The windows of the outhouse are all single-pane windows, and the insulating layer of sawdust beneath the roof is only 0.12 m, compared with 0.30 m in the residence. There are no glass panes in the door, or above it. Apart from these few differences, the physical properties of the envelope elements of the animal house are taken to be the same as those of the residence (*cf.* Table 2). The resulting heat-transmission coefficients (k) and the specific thermal power demand due to transmission losses (Π_{trans}) are displayed below in Table A:2. Note that no solar correction has been made.

Table A:2. Outhouse heat-transmission coefficients and specific thermal power demand due to transmission losses

Envelope elements	(k) [W/m^2K]	Area, (A) [m^2]	(Π_{trans}) [W/K]
Door	2.60	1.7	4.4
Walls	1.27	54.0	68.6
Windows	5.76	3.1	18.0
Roof	0.60	19.8	11.8
Floor	0.39	19.8	7.6
Total	n/a	98.4	110.5
Average	1.12		

The specific thermal power demand due to heat losses caused by ventilation (Π_{vent}) is calculated using an assumed air exchange rate (n) of 1 h^{-1}, which is twice as high as the value estimated for the residence. Because of the odour from the rabbits and pigeons, ventilation needs to be greater in the outhouse. The resulting specific demand is 19.9 W/K.

The wintertime indoor temperature in the outhouse is lower than in the residence. The effective temperature (T_{ei}) is assumed to be 6 °C. Also, the heating season (Z) is shorter, and 150 days is used as an approximation for the calculations made here. Using an average outside temperature (T_{ave}) of –6.8 °C (*cf.* Table 4) and Equation 5, the annual thermal energy demand of the outhouse amounts to 6.0 MWh. The corresponding value for the residence (according to non solar-corrected P(T) modelling) is 19.6 MWh, implying that the combined rabbitry and pigeonry represents 23 % of the heat *demand* of Mr Hua's household.

The annual thermal energy *usage* (including cooking) of Mr Hua's household is covered by 5 tonnes of coal (Hua, 1999-11-08), or 29 MWh[*]. Subtracting 3 MWh for cooking (*cf.* Table 9) leaves a heat usage of 26 MWh to be divided between the residence and the outhouse. The efficiency of the simple coal burner used to heat the outhouse is lower than that of the system of combined kang and hot-water radiators in the residence. 40 % and 70 % may be reasonable estimates (Hao, 1999-11-12). Applying the information given above, Table A:3 shows the results of dividing usage and demand between the residence and rabbitry/pigeonry.

Table A:3. Modelled annual thermal energy usage and demand of the residence and the combined rabbitry and pigeonry

	Heating			Cooking
	Residence	Rabbitry/pigeonry	Total	
Usage [MWh]	17.0	9.1	26.1	3
Demand [MWh]	11.9	3.6	15.5	

[*] Conversion factors for raw coal: 0.7143 tce per tonne and 0.1229 tce per MWh (CESY, 1996).

Appendix B: List of symbols used in the report to designate physical and other quantities

B.1 Latin letters

A = area of envelope element	[m^2]
A_f = total area of doors and windows, or maximum 18 % of floor area	[m^2]
A_o = floor area of building	[m^2]
c = heat capacity	[Wh/kgK, or J/kgK]
d = inner diameter of pipe	[m]
đ = thickness	[m]
D_{hs} = degree-day number per heating season	[K·days]
f_a = annuity factor	[—]
h = distance between pipe centre and ground level	[m]
H = heat density of district-heating grid	[Wh/m]
k = heat-transmission coefficient of envelope element	[W/m^2K]
k_m = average heat-transmission coefficient	[W/m^2K]
L = length of pipe pair (*i.e.* half the total pipe length)	[m]
n = air exchange rate	[h^{-1}]
ņ = economic service life	[years]
P = thermal power	[W]
P_{ra} = power dissipation from return pipe to ground	[W]
P_{sa} = power dissipation from supply pipe to ground	[W]
q_{ih} = specific internal heat gain	[W/m^2]
Q = thermal energy storage capacity	[J]
Q_{del} = heat delivered by the grid	[Wh]
Q_{hs} = thermal energy demand of a heating season	[Wh]
Q_{ih} = heat gain from internal heat (from people, cooking, appliances, *etc.*)	[Wh]
Q_{loss} = heat loss	[Wh]
Q_{supp} = heat supplied to the grid	[Wh]
Q_{trans} = heat loss due to transmission	[Wh]
Q_{vent} = heat loss due to ventilation and infiltration of air	[Wh]
r = inner radius of pipe	[m]
ŗ = interest rate	[—]
r_m = average inner radius of grid pipes	[m]
r_o = outer radius of pipe including insulation	[m]
R = thermal resistance	[m^2K/W]
R_e = external heat transfer resistance to air	[m^2K/W]
R_g = ground resistance	[m^2K/W]
R_i = internal heat transfer resistance to air	[m^2K/W]
R_j = thermal resistance of a plane layer "j"	[m^2K/W]
R_m = average thermal resistance in the grid	[m^2K/W]
R_{pi} = pipe insulation resistance	[m^2K/W]
R_{tz} = resistance due to coinciding temperature zones	[m^2K/W]
s = distance between centres of the two pipes	[m]
T = prevailing outdoor temperature	[°C]
T_a = temperature of ambient ground	[°C]
T_{ai} = average indoor temperature	[°C]
T_{ave} = average outdoor temperature during a heating season	[°C]
T_b = base temperature used for calculating degree-days	[°C]
T_{ei} = effective indoor temperature	[°C]

T_i = desired indoor temperature	[°C]
T_m = average temperature of the grid medium	[°C]
T_r = temperature of return pipe medium	[°C]
T_s = temperature of supply pipe medium	[°C]
T_{store} = temperature of storage medium	[°C]
v = flow velocity of medium	[m/s]
V = volume	[m^3]
V_{inf} = infiltration rate	[m^3]
Z = duration of a heating season	[days]

B.2 Greek letters

α_1 = correction factor for heat storage (in the ground)	[—]
α_2 = correction factor for standard indoor temperature	[—]
α_{sol} = solar-correction term	[W/m^2K]
δk = correction term for model imperfections	[W/m^2K]
Δp_L = specific pressure drop	[Pa/m]
ΔT = temperature difference	[K]
ε = solar correction coefficient for envelope element	[—]
η = efficiency coefficient of heat exchanger for heat recovery	[—]
$\theta_{\bullet a}$ = temperature difference between pipe medium and the ground	[K]
$\int\theta_{ma}dt$ = degree-time number for heat distribution	[Kh]
λ = heat conductivity coefficient	[W/m,K]
λ_g = heat conductivity coefficient of the ground	[W/m,K]
λ_{pi} = heat conductivity coefficient of pipe insulation	[W/m,K]
Λ = friction coefficient of pipe	[—]
Π_{trans} = specific thermal power demand due to heat transmission losses	[W/K]
Π_{vent} = specific thermal power demand due to heat losses through ventilation	[W/K]
ρ = density	[kg/m^3]
Φ = flow of grid medium	[m^3/s]

Appendix C: List of abbreviations and acronyms used in the report (including non-SI units)

ave.	average
CCICED	China Council for International Co-operation on Environment and Development
CESY	China Energy Statistical Yearbook
CNY	Chinese yuan
corr.	correction
CREY	China Rural Energy Yearbook
CSY	China Statistical Yearbook
DOT	Dimensioning Outside Temperature
E	east
EOT	Extreme Outside Temperature
EPA	Environment Protection Agency
GWh	gigawatt-hour
hh	household
JPERI	Jilin Province Energy Resources Institute
kcal	kilocalorie
kgce	kilogram carbon equivalent
kW_e	kilowatt, electric power
kW_{th}	kilowatt, thermal power
kWh	kilowatt-hour
LPG	Liquefied Petroleum Gas
Mtce	million tonnes carbon equivalent
MWh	megawatt-hour
MWh_{th}	megawatt-hour, thermal energy
N	north
n/a	not applicable
pers.	person
PEX	linked polyethylene
S	south
SCB	Statistics Sweden
SEK	Swedish krona
SIS	Swedish Institute for Standards
SS	Swedish Standard
STP	Standard Temperature and Pressure
tce	tonne carbon equivalent
TWh	terawatt-hour
UNDP	United Nations Development Programme
UNF	United Nations Foundation
USA	United States of America
W	west
Wh	watt-hour

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Appendix E: List of selected names of persons and places in English, Chinese characters, and Chinese pinyin with tonal indications

English	***Characters***	***Pinyin***
Baicheng	白城	Báichéng
Beijing	北京	Běijīng
Cao Jiaxing	曹家兴	Cáo Jiāxīng
Changchun	长春	Chángchūn
Chen Heping	陈和平	Chén Hèpíng
China	中国	Zhōngguó
Hao Yongzhuang	郝勇壮	Hǎo Yǒngzhuàng
Hebei	河北	Héběi
Hechengli	合成利	Héchénglì
Heilongjiang	黑龙江	Hēilóngjiāng
Hua Jisheng	华继升	Huà Jìshēng
Inner Mongolia	内蒙古	Nèi Měnggǔ
Jia Huiqing	贾惠清	Jiǎ Huìqīng
Jiang Zhongyi	蒋忠义	Jiǎng Zhōngyì
Jilin	吉林	Jílín
Korea	朝鲜	Cháoxiān
Li Jingjing	李京京	Lǐ Jīngjīng
Li Yuzong	李玉宗	Lǐ Yùzōng
Liaoning	辽宁	Liáoníng
Liudao River	六道河	Liúdào Hé
Liu Guoxi	刘国喜	Liú Guóxǐ
Liu Shuying	刘淑莹	Liú Shūyíng
Longjing	龙井	Lóngjǐng
Mao Yushi	茅于轼	Máo Yúshi
Niu Yulin	牛玉林	Niú Yùlín
Qiang Jian	强健	Qiáng Jiàn
Russia	俄国	Éguó
Shandong	山东	Shāndōng
Shijiapu	十家堡	Shíjiāpu
Shijiazhuang	石家庄	Shíjiāzhuāng
Tang Zhenxu	唐真旭	Táng Zhēnxù
Vladivostok	海参崴	Hǎishēnwǎi
Xinhuatun	新化屯	Xīnhuàtún
Yanbian	延边	Yánbiān
Yang Guanglu	杨广路	Yáng Guǎnglù
Yin Tianyou	尹天佑	Yǐn Tiānyòu
Zhao Li	赵力	Zhào Lì
Zhao Qing	赵青	Zhào Qīng

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