Sustainable Swine Nutrition

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1 2013

2 Energy and Energy Metabolism in Swine

Jean Noblet and Jaap Van Milgen

Introduction

The cost of feed represents an important part of the total cost in swine production (>60%), and within that cost energy is the most expensive component. This economic importance and the effects of energy on animal performance have led to the development of different systems to express the energy value of feeds and the energy requirements of animals. In addition, the competition for feed ingredients among different animal-production sectors and the use of these ingredients for biofuel production and human nutrition can occur alongside efficient production systems with low environmental impact. However, this requires the definition of energy values of feeds and energy requirements of animals to provide effective facilitation for improved sustainability.

The objectives of this chapter are (1) to describe the different steps of energy utilization in swine with a description of available energy systems for evaluating the feeds; (2) to quantify the different types of energy requirements in swine production and the response of growing, or reproductive, pigs to energy intake; and (3) to consider some aspects of energy intake and their regulation by feed characteristics, animal characteristics, and environmental factors. The international unit for expressing energy is the joule (J), which will be used in this chapter, although some nutritionists feel more comfortable in expressing energy as calorie (1 cal = 4.184 J).

Energy Utilization in Swine

Methodological Aspects

Not all gross energy that is consumed will be retained by the animal; there will be losses via feces, urine, gas, and heat. Based on these losses during the process of energy utilization, different energy values and energy systems have been defined: digestible energy (DE) is the difference between gross energy (GE) intake and energy losses in feces; metabolizable energy (ME) is the difference between DE intake and energy losses in urine and gases of digestive fermentation; and net energy (NE) is the difference between ME intake and heat increment (HI).

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Gross Energy

The heat of combustion, or GE, is the most basic form in which energy can be expressed and is a property of the feed itself. The GE content of a feedstuff can be measured in a bomb calorimeter. A small quantity of feed is completely oxidized and the heat release is measured. The GE content of raw materials varies greatly and ranges from about 15 kJ/g DM for sugar cane molasses to 39 kJ/g DM for oils and fats (Sauvant et al., 2004). The difference in GE content between feeds is due to differences in chemical composition. Of all organic components, carbohydrates (i.e., starch, sugars, and dietary fiber) have a relatively low GE content, whereas fat has a very high GE content. In the absence of a bomb calorimeter, the GE values may be estimated from the chemical composition by prediction equations. The INRA-AFZ Tables (Sauvant et al., 2004) proposed the following equation:

$$\mathrm{GE} = 17.3 + 0.0617\ \mathrm{CP} + 0.2193\ \mathrm{EE} + 0.0387\ \mathrm{CF} - 0.1867\ \mathrm{ash} \tag{2.1}$$

where GE is in MJ/kg DM and CP, EE, CF, and ash are the crude protein, ether extract (fat), crude fiber, and ash fractions, respectively, in the diet as percentages of DM. Alternatively, GE (kJ) can be predicted directly by an equation that includes all nutrients (g) providing energy. The following equation was obtained from data of Noblet et al. (2004):

$$\mathrm{GE} = 23.0\ \mathrm{CP} + 38.9\ \mathrm{EE} + 17.4\ \mathrm{starch} + 16.5\ \mathrm{sugars} + 18.8\ \mathrm{NDF} + 17.7\ \mathrm{residue} \tag{2.2}$$

where residue is the difference between OM and the other identified fractions in the equation. As can be seen from this equation, the energy values are lowest for carbohydrates, intermediate for proteins, and highest for lipids. Although Equation 2.2 is an empirical equation, it reflects the energy value of individual nutrients very well. For example, the difference in energy values between starch and sugars is mainly related to the degree of polymerization of carbohydrates. Glucose has an energy value of 15.7 kJ/g (180 g/mole). A long-chain polymer of glucose will have the same energy value per glucose unit, but will weigh less due to release of water during the polymerization ($180 - 18$ g/mol). The theoretical energy value of a long-chain glucose polymer would thus be $15.7 \times 180/(180 - 18) = 17.4$ kJ/g. Some variation in energy values can exist depending on the amino acid composition of protein and, to a lesser extent, the fatty acid composition of lipids. For amino acids, the GE values range from 14 kJ/g for aspartate to 31.6 kJ/g for leucine, isoleucine, and phenylalanine (van Milgen, 2002).

Digestible Energy

The DE content of a feed corresponds to its GE content minus energy losses after digestion in the digestive tract and is obtained as GE minus the energy lost in the feces. Even though they are related to digestion, energy of gas and heat originating from hindgut fermentation are not considered “lost” in the calculation of DE. The ratio between DE and GE corresponds to the digestibility coefficient (DCe) of energy. The DE content is usually measured in pigs kept in digestibility cages; the quantity of feces is either obtained from total collection over a minimum of five days or estimated by using indigestible markers in the feed. For complete feeds or ingredients that can be fed alone (e.g., cereals), a direct measurement of DE content is possible. However, many ingredients can only be included in limited amounts in a feed, either to ensure toleration by the pig or to ensure practical levels of inclusion. In these instances, either the difference method or the regression method is used. With the difference method, the DE contents of two diets are measured. A control diet is used providing the majority of the ingredients. A second diet is prepared based on the control diet and includes the ingredient to be evaluated, using a single level of inclusion. It is assumed that the difference in the measured DE contents between both diets is due to the test ingredient only. It is also assumed that the minerals and vitamins (MV) fraction of the diet does not provide energy, even though the DCe depends on the ash content in the diet (as discussed further on). Therefore, it is important to have a constant MV fraction in the control and experimental diets. The DCe of the test ingredient, then, is calculated as follows:

$$\text{DCe, \%} = 100\,[\text{DEexp} - \text{DEcrtl} \times \text{\%crtl}/(1 - \text{MV0})]/[\text{GEexp} - \text{GEcrtl} \times \text{\%crtl}/(1 - \text{MV0})] \quad (2.3)$$

where GEexp and DEexp are the GE and DE of the experimental diet (MJ/kg DM), GEcrtl and DEcrtl are GE and DE of the control diet (MJ/kg DM), MV0 is the percentage of MV in the control diet (DM as % of DM) and %crtl is the percentage of the control diet (i.e., control diet minus its MV content, or MV0) in the experimental diet. The DE value is then calculated as GE as measured in the lab multiplied by DCe estimated according to Equation 2.3. In such trials, the same control diet can be used for several experimental diets containing different ingredients to be tested or the same ingredient at different inclusion levels. Finally, as for feeds when no calorimeter is available, the GE content of feces can be calculated from the fecal proximate composition. The following equation has been proposed by Noblet and Jaguelin (unpublished data):

$$\text{GE feces} = 18.73 - 0.192\ \text{Ash} + 0.223\ \text{EE} + 0.065\ \text{CP} \quad (2.4)$$

with GE as MJ/kg of DM and chemical composition as a percentage of DM.

Metabolizable Energy

The ME content of a feed is equal to the difference between DE content and energy losses in urine and gases (mainly methane in pigs). The energy content of urine can be measured with pigs kept in metabolism crates. However, such a measurement is laborious and too time consuming to be used on a routine basis. Equations for predicting urinary energy (MJ per kg feed DM) have been proposed for growing pigs and adult sows, respectively (Le Goff and Noblet, 2001; Noblet et al., 2004):

$$\text{Urinary energy} = 0.19 + 0.031\ \text{Nuri} \quad (2.5)$$

$$\text{Urinary energy} = 0.22 + 0.031\ \text{Nuri} \quad (2.6)$$

where Nuri is the N content in the urine, expressed as g of N per kg DM feed intake. The excretion of N in the urine depends on the difference between digestible N and retained N or, in other words, the quantity of protein in the feed and the capacity of the pig to retain energy as protein. Therefore, the urinary energy can vary according to the physiological stage of the pig and diet characteristics. For practical purposes and to apply a single ME value to a feed or raw material, it is suggested to calculate standardized urinary energy losses and standardized ME values for a urinary N loss calculated as a constant proportion of digestible N or total N.

The measurement of methane production necessitates the pig to be housed in a respiration chamber. In addition, the energy loss as methane is small in piglets and growing pigs and can therefore be neglected in most situations. However, in adult pigs where hindgut fermentation is more important (as discussed further on), methane production is four to five times greater than in growing pigs and thus deserves consideration in ME evaluation.

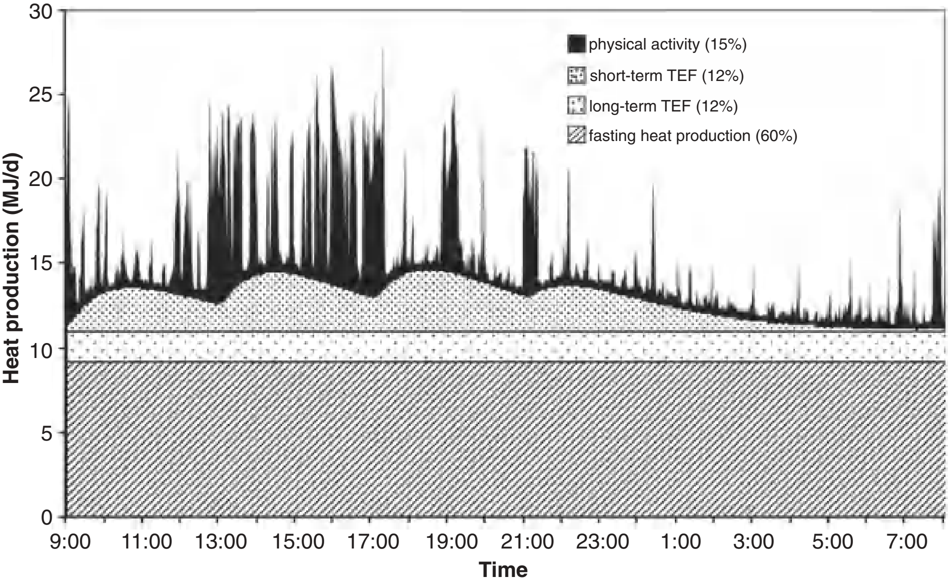

Figure 2.1 Components of heat production in a growing pig (60 kg) offered 2.4 MJ ME/(kg $BW^{0.60}\bullet d$) in four meals at 0900, 1300, 1700, and 2100 hours (TEF = thermic effect of feeding; adapted from van Milgen and Noblet, 2000).

Net Energy

Net energy is defined as the ME content minus HI associated with feed utilization (i.e., the energy cost of ingestion, digestion, and metabolic utilization of ME) and the energy cost corresponding to a “normal” level of physical activity (Figure 2.1). The NE-to-ME ratio (or k) corresponds to the efficiency of ME utilization for NE; it also corresponds to 1 − (HI/ME). However, the HI-to-ME ratio of a given feed depends on the ME intake and also on several physiological factors. For instance, the HI is lower for ME supplied below the maintenance-energy requirement than for ME supplied above the maintenance-energy requirement (Noblet et al., 1993; 1994a,b; Birkett and de Lange, 2001). The HI is also lower when ME is used for fat deposition compared with protein deposition (Noblet et al., 1999). As the proportion of fat deposition typically increases more rapidly than the protein deposition with increasing ME intake, the HI/ME should, at least theoretically, be lower at higher levels of ME intake. To maintain the concept of a single NE value for a given feed or raw material, it is necessary to determine this value under standardized conditions: at protein and amino acid supplies meeting the requirement, at a constant composition of the gain, and/or at a given physiological stage.

For growing pigs, NE intake is usually calculated as the sum of retained energy (RE) at a given production level and the fasting heat production at zero activity (FHP; Noblet et al., 1994a). This NE value and the corresponding k value then correspond to a combined utilization of energy for meeting requirements for maintenance and growth. The RE is either measured by the comparative slaughter technique or, more frequently, calculated as the difference between ME intake and HP estimated by calorimetry. The FHP is either measured directly in fasting animals or obtained from literature data. It can also be calculated by extrapolating HP measured at different feeding levels to zero ME intake (Figure 2.2; FHPr). However, even though it has been widely used in the past, the latter method has important limitations. First, it consists of extrapolating HP measured at feed intake levels typically

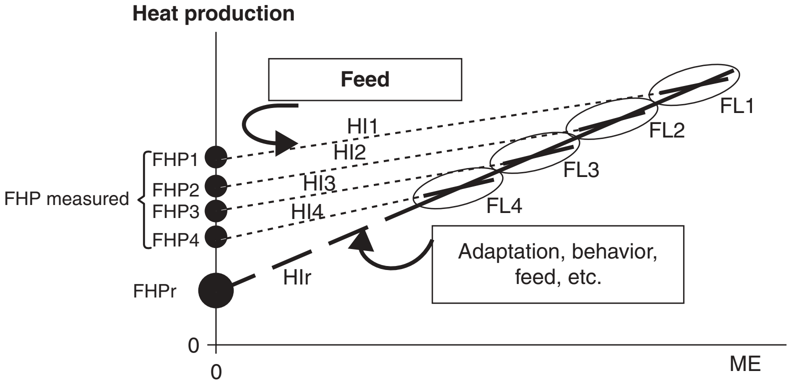

Figure 2.2 Schematic representation of the effect of feeding level (FLi) on heat production and fasting heat production (FHP) in nonruminant animals. Each FHPi corresponds to the FHP measured on animals receiving the FLi during the immediately preceding period. The FHPr (r for regression) is obtained from the regression between HP and ME. The slope is the "regression" heat increment (HIr), and the slope between each FHPi and HPi corresponds to the measured heat increment (HIi). (Aadapted from Koong et al., 1982; de Lange et al., 2007; and Labussière et al., 2009b; 2011.)

ranging 60–100% of ad libitum to HP at zero feed intake, with subsequent inaccuracies in the slope and intercept. Second and more important, the measured FHP is not constant and is affected by the feeding level prior to fasting, especially in growing animals (Koong et al., 1982; de Lange et al., 2006; Labussière et al., 2011). Apparently, the animal adapts its basal energy expenditure to the level of feed intake and/or growth intensity. These authors also observed that FHPr was markedly lower than measured FHP with subsequent lower values for NE and k, and a higher HI (Figure 2.2). They also observed that HI, calculated as HP minus the measured FHP and expressed per unit of ME, is constant for different feeding levels. Furthermore, the degree of adaptation of FHP and HP to feeding level also depends on animal characteristics such as the genotype (Renaudeau et al., 2007). Overall, these observations question the use of FHPr as an estimate of FHP for calculating NE values. The measurement of FHP according to indirect calorimetry methods immediately after a fed period is highly preferable (Noblet et al., 2010). If it is not possible to obtain these measurements, literature values of FHP can be used as an alternative. The HP also depends on climatic factors with an increased HP and reduced RE if the animals are kept below thermoneutrality. It is, therefore, recommended to keep the animals above thermoneutrality to avoid bias in estimating NE and k.

From a practical point of view, and to avoid bias in the calculation of NE for different feeds, it is necessary to carry out energy balance measurements in similar animals (i.e., same sex, same breed, and in the same body-weight range), keep these animals within their thermoneutral zone, minimize variation in behavior, and feed the animals at about the same feed intake level with balanced diets so that the animals can express their growth potential. Under these circumstances, an erroneous estimate of FHP will affect the absolute NE value, but not the ranking between feeds. This also means that NE should not be measured in animals fed ingredients for which the chemical characteristics are very different from those of a complete and balanced diet.

While measurements of DE and, to a lesser extent, ME are relatively easy and can be undertaken on a large number of feeds at a reasonable cost, the actual measurement of NE is far more complex and expensive. The best alternative is to use reliable NE prediction equations established from measurements carried out under similar and standardized conditions. In our laboratory, we have proposed prediction equations to estimate the NE value of ingredients and complete diets for pigs based on DE or ME content, combined with information on chemical characteristics (Noblet et al., 1994a; as discussed further on). Different predictors (i.e., independent variables) originating from measured chemical composition, existing feeding tables, or digestibility trials can be used.

Heat production can be measured directly through direct calorimetry, estimated from gas exchanges through indirect calorimetry, or calculated as the difference between ME intake and energy gain obtained by the comparative slaughter technique. The latter technique can easily be used in small animals such as poultry, but is much more difficult to perform and less accurate in large animals. As such, the most commonly used method for pigs is indirect calorimetry, which consists of measuring oxygen consumption, and carbon dioxide and methane production. These measurements, combined with the urinary energy production, are then used to calculate HP (Brouwer, 1965). This method also allows measurements over a short period of time (e.g., a few days) with possibilities of combination of measurements at different feeding levels (including fasting) on the same animal without adaptation. Modeling methods can be implemented to partition the total daily HP between different components, which can be used in the further interpretation of energy balance data (van Milgen et al., 1997; Figure 2.1).

In conclusion, the NE value of a feed and the corresponding k value should be evaluated according to standardized and adequate methods. The values are dependent on assumptions (FHP), conditions of measurement (e.g., climate, activity) and the composition of the energy gain. This means that data on NE and k available in the literature for pigs should be interpreted with caution and may not be directly comparable. The same comment can be applied to ME values, which depend of the importance of protein catabolism and, to a lesser extent, the inclusion of gas energy losses.

Digestive Utilization of Energy

Effect of Diet Composition

For most pig diets, DCe varies between 70% and 90% but the variation is larger for feed ingredients (10–100%; Sauvant et al., 2004). Most of the variation of DCe is related to the presence of dietary fiber (DF), which is less digestible than other nutrients (<50% versus 80–90% for fat or protein and 100% for starch and sugars; Tables 2.1 and 2.2) and reduces the apparent fecal digestibility of other

Table 2.1 Effect of fiber origin on its digestibility in growing pigs[1].

	Fiber source			
	SBP	SBH	WB	WS
Digestibility[2], %				
NDF	60.1	67.9	40.4	15.0
ADF	54.0	62.2	19.0	11.2
NSP	69.5	79.1	45.8	16.3
Change in DCe[3]	−0.80	−0.83	−1.25	−1.77

[1] Adapted from Chabeauti et al. (1991).

[2] Starch in a basal diet was partly replaced by the fiber source in the experimental diets (SBP = sugar beet pulp, SBH = soybean hulls, WB = wheat bran, and WS = wheat straw); NDF = neutral detergent fiber, ADF = acid detergent fiber, and NSP = non-starch polysaccharides.

[3] Decrease in digestibility coefficient of energy (DCe, %) per 1% increase in NSP.

Table 2.2 Digestibility coefficients of fiber fractions and energy in high-fiber ingredients in growing pigs (G) and adult sows (S)[1,2].

	WB		CB		SBP	
Digestibility, %	G	S	G	S	G	S
NSP	46	54	38	82	89	92
NCP	54	61	38	82	89	92
Cellulose	25	32	38	82	87	91
Dietary fiber	38	46	32	74	82	86
Energy	55	62	53	77	70	76

[1] Adapted from Noblet and Bach Knudsen (1997).

[2] WB = wheat bran, CB = corn bran, SBP = sugar beet pulp, NSP = non-starch polysaccharides, and NCP = non-cellulose polysaccharide; dietary fiber = NSP + lignin.

dietary nutrients such as crude protein and fat (Noblet and Perez, 1993; Le Goff and Noblet, 2001). Consequently, DCe of a feed is linearly and negatively related to its DF content (Tables 2.1 and 2.3). The coefficients relating DCe to DF (Table 2.1; Equation 2.7 in Table 2.3) are such that NDF, or total DF, essentially dilutes the diet, at least in growing pigs. Although DF is partly digested by the growing pig (Tables 2.1 and 2.2), it provides little DE to the animal.

The digestive utilization of DF varies with its botanical origin (Tables 2.1 and 2.2), with subsequent variable effects on energy digestibility. Therefore, the DCe prediction equations presented in Table 2.3 represent average equations for mixed feeds that should not be applied to raw materials where specific relationships are to be used (Noblet et al., 2003). Finally, Equation 2.8 (Table 2.3) indicates that minerals present in the diet have a negative effect on DCe. This effect is partly related to the minerals associated with DF in some ingredients but also to a direct effect (perhaps the abrasion of gut tissues) of minerals provided by calcium carbonate or phosphates (−0.5% of DCe per 1% additional ash; INRA, unpublished data).

Table 2.3 Effect of diet composition (% DM) on energy digestibility coefficient (DCe, %), ME:DE coefficient (%), and efficiency of utilization of ME for NE of mixed diets for growth (k_g, %) or maintenance (k_m, %)[1].

Equation		Source[2]
2.7	$DCe = 98.3 - 0.90\ NDF$	1
2.8	$DCe = 102.6 - 1.06\ Ash - 0.79\ NDF$	1
2.9	$DCe = 96.7 - 0.64\ NDF$	1
2.10	$ME/DE = 100.3 - 0.21\ CP$	1
2.11	$k_g = 74.7 + 0.36\ EE + 0.09\ ST - 0.23\ CP - 0.26\ ADF$	2
2.12	$k_m = 67.2 + 0.66\ EE + 0.16\ ST$	3

[1] CF = crude fiber, CP = crude protein, NDF = neutral detergent fiber, EE = ether extract, ST = starch, and ADF = acid detergent fiber.

[2] Sources: 1 = Le Goff and Noblet (2001; n = 77 diets; Equations 2.7 and 2.8 in 60-kg growing pigs and Equation 2.9 in adult sows), 2 = Noblet et al. (1994a; n = 61 diets; 45 kg pigs), and 3 = Noblet et al. (1993; n = 14 diets; adult sows fed at maintenance).

Table 2.4 Effect of pelleting on digestibility coefficient (%) of fat and energy in growing pigs.

Item	Mash	Pellet
Corn/soybean meal diets[1]		
Fat	61.0	77.0
Energy	88.4	90.3
Wheat/soybean meal/full-fat rapeseed diets[2]		
Fat	27.0	84.0
Energy	73.1	87.4
Wheat/corn/barley/soybean meal diets		
Energy[3]	75.8	77.3
Energy		
Corn	87.0	90.0
Full-fat rapeseed	35.0	83.0
Linseed (extruded)[4]	51.0	84.0

[1] Mean of three diets containing 81% corn and 15.5% soybean meal (Noblet and Champion, 2003).

[2] One diet containing 60% wheat, 15% soybean meal, and 20% full-fat rapeseed; rapeseed was coarsely ground (Skiba et al., 2002).

[3] Mean of four diets containing variable amounts of fiber-rich ingredients (wheat bran and sugar beet pulp; Le Gall et al., 2009).

[4] From Noblet et al. (2008).

Effect of Technology

Digestibility of energy can be modified by technological treatments. Pelleting, for instance, increases the energy digestibility of feeds by about 1% (Skiba et al., 2002; Le Gall et al., 2009). However, for some feeds, the improvement can be more important and depends on the chemical and physical (particle size) characteristics of feeds. In the examples given in Table 2.4, the improvement in energy digestibility is mainly due to an improved digestibility of fat provided by corn, full-fat rapeseed, or linseed. Consequently, the energy values of these ingredients depend greatly on the technological treatment. In the specific situation of a high-oil corn (7.5% oil), pelleting increased the DE content by approximately 0.45 MJ per kg (Noblet and Champion, 2003). For coarsely ground full-fat rapeseed, the DE values as mash and after pelleting were 10.0 and 23.5 MJ DE/kg DM, respectively (Skiba et al., 2002). Unfortunately, there is insufficient information in the literature to quantify the improvement of DCe by pelleting or other technologies (e.g., extrusion, acidification, and enzyme addition) on most ingredients used in pig feeds. In addition, information on the impact of technology on the changes in the site of digestion (i.e., small intestine or hindgut) would be needed. It should also be noted that some effects of technology might be negative. For example, overheating during the drying procedures of wet products such as distillers dried grains with solubles (DDGS) can result in a Maillard reaction, thereby reducing the digestibility (Cozannet et al., 2010).

Effect of Body Weight or Physiological Stage

Energy digestibility is affected by factors other than those related to the diet itself. In growing pigs, DCe increases with increasing body weight (BW) (Noblet, 2005; Table 2.5). The largest effect of BW is observed when adult sows fed slightly above maintenance level are compared with growing pigs offered feed close to ad libitum (Fernandez et al., 1986; Noblet and Shi, 1993; Le Goff and Noblet, 2001; Table 2.6). The difference is most important for diets or ingredients with a high DF content (Equations 2.7 and 2.9 in Table 2.3; Table 2.5). The negative effect of DF on DCe then becomes smaller for heavier pigs or adult sows, and DF will have a positive contribution to energy

Table 2.5 Effect of diet composition and body weight on energy digestibility in pigs (%)[1,2,3].

BW, kg	Control diet	+ Corn starch	+ Dietary fiber	+ Rapeseed oil
44	85.3	90.6	71.6	86.0
103	87.2	91.6	75.6	88.7
148	87.2	92.2	78.0	88.9

[1] Adapted from Noblet and Shi (1994).

[2] BW = body weight.

[3] The control diet contained cereals and soybean meal. The other diets were the control diet + 30% corn starch or 8% rapeseed oil or 30% of a mixture of fibrous ingredients (1/4 wheat bran, 1/4 soybean hulls, 1/4 sugar beet pulp, and 1/4 soybean hulls).

supply in heavier pigs. From a large data set of measurements (77 diets), Le Goff and Noblet (2001) calculated that 1 g of NDF provided 3.4 kJ and 6.8 kJ in 60-kg growing pigs and mature sows, respectively. Using the same data, it was also shown that the difference in DE values between adult sows and growing pigs is proportional to the amount of indigestible organic matter measured in the growing pig (4.2 kJ/g on average; Noblet et al., 2004; Figure 2.3).

The improvement in energy digestibility with increasing BW is due to the greater digestibility of the DF fraction (Table 2.2), which is related to a greater digestive capacity of the hindgut in heavier pigs and, more important, a reduced rate of passage in the digestive tract (80 hours in adult sows versus 35 hours in growing pigs; Le Goff et al., 2002). The depressive effect of DF on protein and fat digestibility (i.e., endogenous losses) is also smaller in adult than in growing pigs, which also contributes to the reduced effect of DF on DCe in adult pigs (Le Goff and Noblet, 2001). In lactating sows with a high feed intake capacity (6–9 kg/day), energy digestibility is also higher than in the growing pig (Table 2.7) and the results indicate that difference does not seem to depend on the physiological status or the feeding level of the adult sow. This means that values obtained in adult dry sows at pregnancy feeding levels can be used for both pregnant and lactating sows, and that these values are higher than those obtained in growing pigs (Table 2.7).

The DCe or the DE differences between sows and growing pigs, for a given level of dietary fiber, also depend on the origin of DF or on the physicochemical properties of DF. This is illustrated in Table 2.1 and in Figure 2.3, where the effects of DF from wheat bran, corn bran, and sugar beet pulp are compared. Noblet and Le Goff (2001) presented detailed information on the effect of botanical origin of DF on DCe in both growing pigs and adult sows. These results indicate that growing pigs

Table 2.6 Effects of body weight and physiological stage on energy digestibility in pigs[1].

	Trial 1[2]		Trial 2[3]	
Item	G-pig	Dry sow	G-pig	Lac. sow
BW, kg	60	227	62	246
Feed intake, g DM/d	2,044	2,119	2,062	4,850
Energy digestibility, %	77.2[a]	80.5[b]	79.9[a]	84.9[b]

[1] G-pig = growing pigs, Lac. sow = lactating sow, and BW = body weight.

[2] Mean of three diets based on maize, wheat, barley, peas, soybean meal, and variable proportions of wheat bran, sunflower meal, corn gluten feed, and animal fat (INRA data).

[3] Mean of three diets based on maize, wheat, barley, peas, soybean meal and variable proportions of wheat bran, sunflower meal, corn gluten feed, and animal fat (Etienne et al., 1997).

[a,b] Within a trial, means without a common superscript differ ($P < 0.05$).

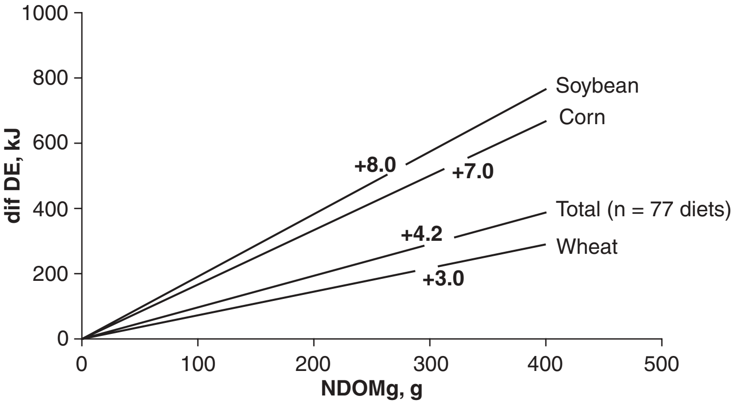

Figure 2.3 Relationship between difference in DE value in adult sows and DE value in growing pigs (dif DE) and indigestible organic matter in growing pigs (NDOMg) for some ingredients. (Adapted from Noblet et al., 2003a.)

have a limited ability to digest DF with small differences between fiber sources, while adult sows digest DF more efficiently but the improvement depends on the chemical characteristics of DF (e.g., level of lignin). The examples presented in Table 2.7 also illustrate the effect of botanical origin with smaller differences between physiological stages for Gramineae (e.g., wheat, barley, wheat bran), Brassicaceae (e.g., rapeseed), or Compositae (e.g., sunflower) and more pronounced differences for Leguminosae (e.g., pea, soybean, lupin), especially for the hull fraction of these grains. The consequence is that the DE difference between adult sows and growing pigs is proportional to indigestible organic matter in growing pigs, but with specific coefficients for each (botanical) family of ingredients (Figure 2.3).

Little information concerning comparative digestibility in piglets and growing pigs is available. Considering that piglets are usually fed highly digestible, low-fiber diets, from a practical point of view, piglets can be considered growing pigs concerning the digestive utilization of energy.

Table 2.7 Digestible energy value (DE) of ingredients for growing pigs and adult sows (as-fed)[1].

	DE, MJ/kg		
Ingredient	Growing pig	Adult pig	a[2]
Wheat	13.85	14.10	3.0
Barley	12.85	13.18	2.5
Corn	14.18	14.77	7.0
Pea	13.89	14.39	6.0
Soybean meal	14.73	15.61	8.0
Rapeseed meal	11.55	12.43	3.5
Sunflower meal	8.95	10.25	3.5
Wheat bran	9.33	10.29	3.0
Corn-gluten feed	10.80	12.59	7.0
Soybean hulls	8.37	11.46	8.0

[1] Adapted from Sauvant et al. (2004).

[2] Kilojoule difference in DE between adult sows and growing pigs per g of indigestible organic matter in the growing pig (also see Figure 2.3).

For growing pigs, especially when they are raised to heavy BW (i.e., late finishing pigs), we should theoretically use energy values adapted to each stage of growth. However, the extent of the improvement is limited, and, for practical reasons, it is recommended to use the same values for growing pigs and piglets, irrespective of their BW. This means that, in practice, two different DE values can be given to feeds: one for piglets and growing pigs, and one for adult sows (Table 2.7; Sauvant et al., 2004a,b). This proposal is especially justified for fibrous ingredients. A consequence of the effect of BW on DCe is that digestibility trials should be carried out at approximately 60 kg BW to be most representative for the overall weaning–growing–finishing period.

Utilization of DE for ME

The ME content of a feed equals the DE content minus the material energy losses in the urine and combustible gases resulting from fermentation (i.e., methane and hydrogen). The energy losses in the urine (mainly as urea) are due to the deamination of amino acids given in excess of what can be deposited. At a given stage of production, urinary nitrogen excretion depends mainly on the protein content of the diet. Consequently, ME:DE is linearly related to the dietary protein content (Equation 2.10 in Table 2.3). In most situations, ME:DE of complete feeds is approximately 0.96. However, this mean value cannot be applied to single feed ingredients and Equation 2.10 cannot be applied beyond the range of typical CP contents of pig diets (10–25%). The most appropriate solution, therefore, is to estimate urinary energy (kJ/kg DM intake) from urinary nitrogen (g/kg DM intake) according to Equations 2.1 and 2.2 and for a retention coefficient of N equal to 50% of digestible N (or 40% of total N; Sauvant et al., 2004).

In growing pigs, average energy loss in methane is equivalent to 0.4% of DE intake (Noblet et al., 1994a). In sows fed at maintenance level, methane production represents a much greater proportion of DE intake (1.5%; Noblet and Shi, 1993) and may reach up to 3% of DE intake in sows fed very high fiber diets (Ramonet et al., 2000). More generally, methane production increases with BW and DF level in the diet (Noblet and Shi, 1993; Jorgensen et al., 2001). A compilation of literature data by Le Goff et al. (2002a) and unpublished data from our laboratory (Noblet et al., 2004) suggest that methane energy is equivalent to 0.67 and 1.33 kJ per g of fermented DF in growing pigs and adult sows, respectively.

Metabolic Utilization of Energy

Effect of Physiological Stage

The utilization of ME is associated with HI or heat loss originating from the energy cost of ingestion, digestion, and some physical activity, in addition to the energy loss associated with metabolic transformations (e.g., the synthesis of lipid from glucose). The efficiency of ME utilization (1 − HI, or k) is either directly measured or, in most situations, obtained according to regression methods. First, k depends on the final utilization of energy with a higher value for fat energy deposition (kf; approximately 80%) than for protein deposition (kp; approximately 60%). Also, the efficiency of using ME below maintenance differs from the utilization above maintenance energy requirements (Noblet et al., 1993; 1994; 1999; Table 2.8). In the case of using ME for maintenance functions, the situation is rather complex. During fasting, animals mobilize body reserves (i.e., protein, lipid, and glycogen) to supply energy for maintenance functions and include the cost of energy mobilization. When the ME supply meets the maintenance requirements (MEm), all nutrients are provided by

Table 2.8 Efficiencies of utilization of ME in swine (%)[1].

Stage	Production	ME component	Efficiency	Source[2]
Adult	Maintenance	ME	77	1
Growth/pregnancy	Protein gain	ME	60	2,4
	Fat gain	ME	80	2,4
	BW gain	ME	74	3
Pregnancy	Uterus gain	ME	50	4
Lactation	Milk	ME	72	5
Growth	BW gain + maintenance	Fat	90	3
		Starch	82	3
		Protein	58	3
		Dietary fiber	58	3

[1] BW = body weight.

[2] 1 = Noblet et al. (1993c), 2 = Noblet et al. (1999), 3 = Noblet et al. (1994b), 4 = Noblet and Etienne (1987b), and 5 = Noblet and Etienne (1987a).

the diet, and the maintenance energy requirement then includes the cost of intake, digestion, and absorption of these nutrients. This means that the k_m (the slope of the line connecting FHP to MEm; Figure 2.2) is a relative efficiency value (i.e., the efficiency of using dietary energy for maintenance relative to the efficiency of using energy from body reserves) rather than an absolute value. The consequence of this is that k_m values can exceed unity: That is, when the efficiency of using dietary energy is greater that that of using energy from body reserves.

Effect of Diet Composition

In a standardized situation in terms of animal characteristics and feeding level (see the *Methodological Aspects* section), k varies with diet composition (Equation 2.11 in Table 2.3). It increases with the addition of dietary fat and starch, and decreases with the addition of fiber and protein. The variations in k in growing pigs are due to differences in efficiencies of ME utilization between nutrients with the highest values for fat (approximately 90%) and starch (approximately 82%) and the lowest (approximately 60%) for DF and crude protein (Schiemann et al., 1972; Just et al., 1983; Noblet et al., 1994; van Milgen et al., 2001). The average k value obtained in 61 diets was 74% and the k value of a standard cereals and soybean meal diet was 75% (Noblet et al., 1994). These differences in efficiencies between nutrients also mean that HI per unit of energy associated with metabolic utilization of energy is higher for crude protein and DF than for starch or ether extract (Table 2.9). Measurements conducted in pigs, which differ in BW and in composition of BW gain, indicate that the efficiency of utilization of ME is little affected by the composition of BW gain under most practical conditions with a similar ranking between nutrients (Noblet et al., 1994b). Furthermore, the measurements conducted in adult sows fed at maintenance energy level indicate that the ranking of k values of nutrients is similar to that observed in growing pigs with absolute values slightly greater (Equation 2.12 in Table 2.3; Noblet et al., 1993; 1994). An interesting aspect of energy efficiency is illustrated in the results of van Milgen et al. (2001) and concerns the HP associated to the utilization of dietary protein for protein deposition or for lipid deposition. The data show that the heat increment associated with both pathways is similar and efficiencies are equivalent. From a practical point of view, this means that the NE value of dietary CP is constant, irrespective of its final utilization.

Table 2.9 Energy value of starch, protein, and fat according to energy systems[1].

Item	Starch	Crude protein[3]	Crude fat[3]
Energy values[2] (kJ/g)			
DE	17.5 (100)	20.6 (118)	35.3 (202)
ME	17.5 (100)	18.0 (103)	35.3 (202)
NE	14.4 (100)	10.2 (71)	31.5 (219)
Heat production, kJ/g	3.1	7.8	3.8

[1] Adapted from Noblet et al. (1994a; n = 61 diets.)
[2] Parentheses = % of starch.
[3] Crude protein and crude fat are assumed to be 90% digestible, whereas starch is assumed to be 100% digestible.

Overall, these results indicate that an increase in dietary crude protein content results in an increased HP (Le Bellego et al., 2001), while the inclusion of fat contributes to a reduction of HP (Noblet et al., 2001). Diets with low crude protein and/or high fat contents can then be considered as low heat increment diets. The effect of DF on HP remains unclear. In some trials, and in agreement with the low efficiency of ME from DF, HP is increased when DF is increased (Noblet et al., 1989; Ramonet et al., 2000; Solund Olesen et al., 2001; Rijnen et al., 2003), whereas in other trials, HP remains constant or even decreases (Rijnen et al., 2001; Le Goff et al., 2002). From a biochemical perspective, HP should increase and most results are consistent with this. However, addition of DF may change the behavior of animals (e.g., reduced physical activity) or the overall metabolism, thereby decreasing HP (Schrama et al., 1998). Furthermore, it is probable that the effects of DF also depend on the nature of DF.

Interaction with Climatic Factors

At ambient temperatures above the lower critical temperature (LCT), pigs dissipate their heat to maintain their body temperature with adjustments of feed intake (see *Energy Requirements for Thermoregulation* section). Below LCT, pigs reduce the dissipation of heat to their environment but have to increase their HP to maintain homeothermy. In that situation, HI is not a loss of energy and contributes to covering the energy requirement to maintain homeothermy (Quiniou et al., 2001). This high HI is observed with high protein or high DF feeds. High protein diets are seldom used because of their high cost and their negative environmental impact. Therefore, only high DF feeds can be a potential solution for meeting thermoregulation energy requirements. Data in Table 2.10 confirm this possibility with a special interest in gestating sows that are able to degrade high DF

Table 2.10 Effect of dietary fiber level and ambient temperature on utilization of energy in pregnant sows[1,2,3].

Item	Control diet	+ Straw	+ Alfalfa
ME intake, MJ/d	29.6 (100)	32.0 (108)	34.0 (115)
Heat production, MJ/d			
At 21.5°C	26.2 (100)	27.1 (103)	26.9 (103)
At 10.5°C	34.9 (100)	34.6 (99)	34.5 (99)

[1] Adapted from Noblet et al. (1989b).
[2] Parentheses = % of the control diet.
[3] All sows received the same amount of the control diet; sows in experimental treatment received a daily supplement (600 g) of straw or alfalfa. Mean body weight of sows was 205 kg.

feeds (see *Digestive Utilization of Energy*), are fed below their voluntary feed intake capacity, and frequently housed at temperatures below their LCT (<20°C).

Energy Evaluation Systems

Digestible and Metabolizable Energy

Apart from direct measurement in pigs, the DE value of raw materials can be obtained from the literature (Stein et al., 2007) or from feeding tables (NRC, 1998; Sauvant et al., 2004). The utilization of table values should be restricted to ingredients having chemical characteristics similar to those actually used. The effect of variation in chemical composition can be taken into account by using prediction equations of DCe or DE content of families of ingredients (Noblet et al., 2003; www.evapig.com). As illustrated in the previous section, DCe is affected by animal BW. It is therefore appropriate to use DE values adapted to each situation. From a practical point of view, it is suggested to use two DE values, one for "60-kg" pigs, which can be applied to piglets and growing–finishing pigs, and one for adult pigs, which is applicable to both pregnant and lactating sows. Values given in most feeding tables are typically obtained from 30- to 60-kg pigs and are therefore not applicable to adult pigs. A methodology based on the fact that the difference in DE between adult and growing pigs is proportional to the amount of indigestible OM in the growing pig has been proposed by Noblet et al. (2003) for estimating DE values in adult pigs from DE values in growing pigs (Figure 2.3). It has been implemented in the tables proposed by Sauvant et al. (2004) and some examples are given in Table 2.7.

The DE content of compound feeds can be obtained by adding the DE contributions of ingredients and assuming that there is no interaction, an assumption that seems to hold in most instances (Noblet and Shi, 1994). When the actual composition of the feed is unknown, it is possible to use prediction equations based on chemical criteria (Noblet and Perez, 1993; Le Goff and Noblet, 2001):

$$\text{DE, MJ/kg DM} = 17.69 + 0.146\ \text{EE} + 0.071\ \text{CP} - 0.132\ \text{NDF} - 0.341\ \text{Ash} \tag{2.13}$$

where chemical criteria are expressed as % of DM, and EE and CP are ether extract and crude protein, respectively. The equation obtained and applicable for complete feeds cannot be used for ingredients.

Other possibilities with near infrared or in vitro methods (Boisen and Fernandez, 1997; Noblet and Jaguelin-Peyraud, 2007) have been proposed for estimating the DE value of feeds. Some tables provide estimates of the content of digestible nutrients obtained as the product of nutrient content and (a constant) digestibility coefficient. When this information is available, the DE content can be estimated according to the following equation:

$$\text{DE, MJ/kg DM} = 0.232\ \text{DCP} + 0.383\ \text{DEE} + 0.174\ \text{Starch} + 0.162\ \text{Sugars} + 0.178\ \text{DRes} \tag{2.14}$$

where DCP and DEE are the digestible crude protein and digestible crude fat contents, respectively, and DRes is the digestible residue calculated as the difference between digestible OM and the sum of other nutrients considered in the equation (% of DM; Le Goff and Noblet, 2001). The DE can also be estimated directly from the average contribution of all crude nutrients in OM of feed according to the following equation (Le Goff and Noblet, 2001):

$$\text{DE} = 0.225\ \text{CP} + 0.317\ \text{EE} + 0.172\ \text{Starch} + 0.032\ \text{NDF} + 0.163\ \text{Residue} \tag{2.15}$$

with “Residue” as the difference between OM content and the other nutrients considered in the equation (% of DM). In all equations or predictions, DF has an important impact on the accuracy of the prediction. Equations 2.14 and 2.15 can be applied to raw materials and compound feeds but with inaccuracies, due to their inability to consider the nature of DF and, to a smaller extent, the composition of fat.

The approaches for predicting ME values of pig feeds are similar to those described for DE. However, because direct ME measurements are not carried out routinely and ME values depend on protein catabolism, it is suggested to calculate ME values from DE values and standardized urinary energy losses (Equation 2.5 for growing pigs).

Net Energy

All published NE systems for pigs combine the utilization of ME for maintenance and for growth (Just et al., 1983; Noblet et al., 1994) or for fattening (Schiemann et al., 1972) by assuming similar efficiencies for maintenance and energy retention. The system used in the Netherlands (CVB, 1994) has been adapted from the equations proposed by Schiemann et al. (1972) and literature data. The system used by NRC (1998) for estimating NE values combines results from direct measurements using the piglet as a model for all swine production stages (Galloway and Ewan, 1989) and measurements mostly carried out on ingredients (and therefore unbalanced feeds). Emmans (1994) proposed a generic model based on corrections applied to the ME content. More recently, Boisen and Verstegen (1998) suggested new concepts for estimating the NE value of pig feeds (so-called physiological energy) based on the combination of in vitro digestion methods for estimating digestible nutrients and biochemical coefficients for evaluating the ATP production potential from the nutrients.

The system proposed by Noblet et al. (1994) is based on a large set of measurements (61 diets) and regression analysis; FHP was assumed constant (750 kJ/kg $BW^{0.60}$/d) in the calculation of NE, which was calculated as FHP + Retained energy. The prediction equations are listed in Table 2.11. These equations have been validated in further calorimetry trials conducted in our lab (Le Bellego et al., 2001; Noblet et al., 2001; van Milgen et al., 2001; Noblet, 2005). The equations are based on information available in conventional feeding tables and they are applicable to single ingredients and compound feeds and at any stage of pig production. It is important to point out that different DE values or digestible nutrient contents should be used in growing–finishing pigs and adult sows with two subsequent NE values. Reliable information on digestibility of energy or of nutrients is,

Table 2.11 Equations for prediction of DE, ME, and NE in feeds for growing pigs (61 diets; MJ/kg dry matter and % of DM)[1].

Number	Equation[2]
2.16	$DE = 0.232 \times DCP + 0.387 \times DEE + 0.174\ ST + 0.168\ SU + 0.167\ DRes$
2.17	$ME = 0.204\ DCP + 0.393\ DEE + 0.174\ ST + 0.165\ SU + 0.154 \times DRes$
2.18	$NEg(2) = 0.121\ DCP + 0.350\ DEE + 0.143\ ST + 0.119\ SU + 0.086\ DRes$
2.19	$NEg(4) = 0.703\ DE - 0.041\ CP + 0.066\ EE - 0.041\ CF + 0.020\ ST$
2.20	$NEg(7) = 0.730 \times ME - 0.028 \times CP + 0.055 \times EE - 0.041 \times CF + 0.015 \times ST$

[1] Adapted from Noblet et al. (1994c).

[2] DCP = digestible crude protein (CP), EE = ether extract, DEE = digestible EE, ST = starch, SU = sucrose, and DRes = digestible residue (i.e., difference between digestible organic matter and other digestible nutrients considered in the equation).

Table 2.12 Relative DE, ME, and NE values of ingredients for growing pigs[1,2].

Item	DE	ME	NE	NE/ME, %
Animal fat	243	252	300	90
Corn	103	105	112	80
Wheat	101	102	106	78
Reference diet	*100*	*100*	*100*	*75*
Pea	101	100	98	73
Soybean (full-fat)	116	113	108	72
Wheat bran	68	67	63	71
Soybean meal	107	102	82	60

[1] Adapted from Sauvant et al. (2004).

[2] Within each system, values are expressed as percentages of the energy values of a diet containing wheat, soybean meal, fat, wheat bran, peas, and minerals and vitamins.

therefore, necessary for prediction of the NE content of feed for pigs. In fact, this information is the most limiting factor for predicting energy values of pig feeds.

Noblet and van Milgen (2004) have discussed the limits of the different NE systems and their comparisons. In brief, the energy system proposed initially by Noblet et al. (1994) was the most appropriate for prediction of NE value of pig feeds and performance of animals. The NE values proposed by NRC (1998) were quite different, especially for some ingredients, from the NE values proposed by most other systems.

Comparison of Energy Systems

The efficiency of ME utilization for NE differs greatly between nutrients (Table 2.9; Equations 2.16 to 2.18 in Table 2.11). It is, therefore, logical that the hierarchy among feeds obtained in DE or ME systems can be different from that obtained in the NE system. Because NE represents the best compromise between the energy value (a property of the feed) and energy requirement (a property of the animal), the energy value of protein or fibrous feeds will be overestimated when expressed on a DE (or ME) basis. On the other hand, fat or starch sources are underestimated in a DE (or ME) system (Table 2.12).

The quality of a nutritional evaluation system is given by its ability to predict the response of the animals in terms of units of feed per unit of performance and independently of the diet composition (or specific effects of nutrients). With regard to energy evaluation systems, data presented in Table 2.13 illustrate the relationship between the energy system and energy cost of BW gain and confirm that NE as calculated according to Noblet et al. (1994) is a better predictor of performance than DE or ME. In other words, the NE value is the most satisfactory estimate of the energy value of feeds.

Conclusion

The energy value of a feed depends primarily on its chemical characteristics. At the DE level, it is mainly determined by its DF content, which acts more or less as a diluent, and by fat, which is very energy-dense. At the ME level, the change is essentially related to the dietary CP content, which affects the urinary N and energy losses. Finally, at the NE stage, most of the difference originates from CP. The impact of nutrient composition on energy values is illustrated in the coefficients of

Table 2.13 Performance of growing–finishing pigs according to energy system and diet characteristics[1,2].

Item	DE	ME	NE
Added fat, % (Trial 1)			
0	100	100	100
2	100	100	100
4	99	99	100
6	98	98	100
Crude protein (30–100 kg; Trial 2)			
Normal	100	100	100
Low	96	97	100
Crude protein (90–120 kg; Trial 3)			
Normal	100	100	100
Low	97	98	100

[1] Adapted from Noblet (2006) and unpublished data.

[2] Energy requirements (or energy cost of body weight gain) for similar daily body weight (BW) gain and composition of BW gain; values are expressed relative to the energy requirement (or energy cost of BW gain) in the control treatment (considered as 100).

Table 2.14 Actual contribution of dietary nutrients to energy supply in growing pigs (kJ/g)[1,2].

Number		CP	Fat	Starch	Sugar	Residue
2.21	GE	22.6	38.8	17.5	16.7	18.6
2.22	DE	22.5	31.8	18.3	16.1	0.5
2.23	ME	19.7	32.2	18.2	15.9	0.5
2.24	NE	11.8	28.9	14.8	11.5	−0.9

[1] From recalculations of data of Noblet et al. (1994).

[2] Measurements were collected from 61 diets fed to 45-kg pigs and coefficients were obtained from multiple linear regression equations (without intercept). Residue corresponds to the difference between organic matter and the sum of CP, fat, starch, and sugars.

equations presented in Table 2.14, with the highest contribution to NE of fat and the lowest for CP. The energy value also depends on technological treatments applied to the feed with most effects concerning the fat fraction of the feed, affecting its digestibility. Finally, energy value depends on the type of animal the feed is offered where the DF fraction makes a greater contribution to the energy value in adult pigs than in growing pigs.

Energy Requirements

Introduction

Energy requirements are expressed on different bases. In pigs offered feed ad libitum, requirements mainly consist of fixing the energy density according to regulation of feed intake (appetite), the growth potential of the pig, climatic factors, or economical considerations. In that situation, it is difficult to precisely define an energy requirement because the animal will attempt to regulate its feed intake to meet its energy requirements. In restrictively fed growing pigs or in reproductive sows, it is necessary to define a feeding level according to anticipated performance or estimated requirements. These recommendations represent average values, which are unable to account for the effects of genotype, production level, climatic environment, or behavior of the animal. In more sophisticated analytical approaches (factorial approach or modeling), the components of energy requirements (e.g., maintenance, physical activity, thermoregulation, growth, and milk production) are determined. This section will deal mainly with the last approach.

Most trials and recommendations from literature were conducted using DE or ME as a basis for expression of requirements. These recommendations have been obtained mostly with conventional feeds: cereals/soybean meal–based diets with an efficiency of ME utilization for NE in growing pigs of about 75% (or 72% for DE). Consequently, the NE requirements (as diet energy density, daily energy requirements, components of energy requirements, etc.) can be obtained by multiplying the DE or ME requirements by 0.72 or 0.75, respectively. Our calorimetry studies have shown that absolute values of efficiencies of ME for NE differed slightly according to BW or genotype in growing pigs (Noblet et al., 1994) or were higher in adult sows fed at maintenance level than in growing pigs (Noblet et al., 1993). The difference did not depend on diet characteristics and the magnitude of the difference in the different situations was identical for all nutrients (Noblet, 2006). This means that NE requirements can be calculated similarly for any stage of pig production, including pregnant or lactating sows or growing pigs with different growth potentials. Because the most reliable and accurate NE equations have been obtained in growing pigs, it is proposed to use these NE equations at all stages of pig production; requirements are then expressed according to a "growing pig" NE value (Noblet, 2006). However, these growing pig NE values should differ according to BW or physiological stage; for simplification, only two NE values should be used, one for growing pigs, including piglets, and one for adult sows, either pregnant or lactating (Sauvant et al., 2004).

Maintenance Energy Requirements

The energy requirement for maintenance (MEm, expressed as ME) is assumed to be proportional to metabolic BW (BW^b). The most appropriate b value is 0.60 in growing pigs (Noblet et al., 1994a; 1999); this exponent is preferred over the commonly used 0.75 exponent, which has been developed for interspecies comparisons or estimations for adult animals within one species. The value to be considered for growing pigs raised indoors and at an environmental temperature within the thermoneutral zone is about 1.00 MJ ME/kg $BW^{0.60}$/d (Noblet et al., 1999). Using an average efficiency value of ME for NE of 75%, this corresponds to a NE requirement for maintenance of 0.750 MJ NE/kg $BW^{0.60}$/d, which is the average value of FHP measured in several trials in our research group (Le Bellego et al., 2001; van Milgen et al., 2001; Noblet et al., 2001; Le Goff et al., 2002; de Lange et al., 2006; Lovatto et al., 2006; Barea et al., 2010) and in other research groups (Koong et al., 1982; Tess et al., 1984).

The energy requirements for maintenance, when expressed per kg of metabolic BW ($BW^{0.60}$), are almost constant over the growth period with small differences between breeds or sexes. Differences are substantial only for extreme breeds with lower values for slow growing and/or fat pigs such as the Meishan breed and with higher values for fast-growing and lean-type pigs (Noblet et al., 1999), or pigs treated with somatotropin (Noblet et al., 1992). Therefore, for most pigs, MEm can be considered as constant under standardized conditions (i.e., conventional housing, thermoneutral environments, and feeding levels close to ad libitum). This maintenance energy requirement includes a standard level of physical activity, which has an average energy cost of 0.200 MJ ME/kg $BW^{0.60}$/d. Approximately half of this cost is due to standing (approximately four hours

Table 2.15 Energy requirements in swine[1].

Stage	Energy requirement, MJ	Source[2]
Growth	MEm = 1.05 × kg $BW^{0.60}$	1
	Energy gain = 23.0 × Protein gain, kg + 39.9 × Fat gain, kg	2
	Energy content lean tissue gain = 8.5–10.5 MJ/kg	2
	Energy content adipose tissue gain = 31–33 MJ/kg	2
	ME thermoregulation See Figure 2.5	3
Pregnancy	MEm = 0.440 × kg $BW^{0.75}$	4
	Energy maternal gain = 9.7 × BW gain, kg + 54 × P2 gain, mm	5
	Energy uterus gain = 4.8 × fetus BW gain, kg	6
	ME per 100 min standing = 0.035 × kg $BW^{0.75}$	7
	ME thermoregulation/°C = 0.010–0.020 × kg $BW^{0.75}$	8
Lactation	MEm = 0.460 × kg $BW^{0.75}$	9
	Energy in milk = 20.6 × Litter BW gain, kg - 0.376 × Litter size	10

[1] See Table 2.8for efficiencies; BW = body weight.

[2] 1 = Noblet et al. (1991; 1999), 2 = Noblet et al. (1999) and Karege (1991), 3 = Quiniou et al. (2001), 4 = Noblet and Etienne (1987b), 5 = Dourmad et al. (1996, 1997; 1998), 6 = Noblet et al. (1985b), 7 = Noblet et al. (1993a), 8 = Noblet et al. (1989b; below 20°C), 9 = Noblet and Etienne (1987a), and 10 = Noblet and Etienne (1989).

per day), while the other half is due to movements during lying (van Milgen and Noblet, 2003). The value of 1 MJ ME/kg $BW^{0.60}$/d for maintenance energy requirements has been obtained in respiration chambers and, therefore, with a reduced level of physical activity and at thermoneutrality. A slightly greater value of MEm of 1.05 MJ ME/kg $BW^{0.60}$/d can be used to account for the greater activity in normal housing production systems (Table 2.15). This value would not be applicable in suckling piglets (Noblet and Etienne, 1987) or in early weaned piglets (Noblet and Le Dividich, 1982), but these specific stages should be revisited according to more appropriate methodologies and to the recent data on thermoregulation and physical activity at these early stages of growth.

In reproductive sows, the MEm requirement is proportional to metabolic BW, using the classical value for the exponent of 0.75. The values measured for pregnant and lactating sows at thermoneutral and "standard" activity levels are given in Table 2.15. The MEm value in lactating sows is higher than in pregnant sows, probably due to a greater production level. Inversely, MEm in pregnant sows is rather variable in connection with variability in levels of physical activity (Noblet et al., 1993; see section on *Energy Cost of Physical Activity*).

Energy Requirements for Growth

From a nutritional point of view, growth corresponds to the deposition of protein, fat, minerals, and water with a subsequent ME requirement for protein and lipid deposition. The ME requirements for body protein or lipid deposition (ME_p) can be estimated from the quantities of deposited protein or lipid and the efficiencies of utilization of ME for energy deposited as protein and fat (k_p and k_f, respectively). For a conventional cereals/soybean meal–diet, Noblet et al. (1999) proposed 60% and 80% for k_p and k_f, respectively. The energy content of body proteins and lipids are approximately 23.8 and 39.5 kJ/g, respectively. The calculated ME requirements are then 40 and 50 kJ ME per g of protein and fat, respectively.

Table 2.16 Chemical composition of tissues and body weight gain in growing pigs, and consequences on energy requirements for tissues gain[1].

	Entire males			Castrated males		
Composition	Lean[2]	Adipose	eBW	Lean	Adipose	eBW
Water, %	69.9	18.7	58.5	65.6	14.9	51.0
Ash, %	1.0	0.2	3.1	1.0	0.2	3.0
Protein, %	17.9	5.4	16.7	18.2	4.1	16.0
Fat, %	10.2	75.4	21.1	15.3	81.8	30.4
Energy, kJ/g	8.5	31.3	12.3	10.4	33.3	15.6
ME requirement[3], kJ/g	12.2	39.8	17.2	14.9	42.6	21.6

[1] Adapted from Noblet et al. (1994) and J. Noblet (unpublished data); over the 20–95 kg body weight (BW) period and based on the comparative slaughter technique.

[2] Lean = including intermuscular fat; eBW = empty BW.

[3] Calculated as 40 and 50 kJ ME/g of protein and fat, respectively.

From technical and economical points of view, the growth of tissues, such as increasing lean tissues and reducing adipose tissues in the carcass concomitantly, is important. Measurements of chemical composition of lean and adipose tissues weight gain, and the associated feed energy costs calculated according to the previous discussion, indicate that the feed cost of adipose tissue gain is about 3.5 times the cost of lean tissue gain (Table 2.16). The consequence of these major differences in energy content and energy requirement for tissues gain in pigs is that the ME requirement for BW gain depends directly on the lean-to-adipose ratio in BW gain or lipid content. The protein content of BW gain is relatively constant (16–17%) in most practical situations of pig production.

The chemical and tissue composition of BW gain in growing pigs depends on several factors that will not be studied in detail in this chapter. In brief, the energy content of BW gain is lower in lean-type pigs than in obese-type pigs, lower in males than in females or in barrows, lower in lighter than in heavier growing-finishing pigs, and lower in energy-restricted than in ad libitum fed pigs (Campbell and Taverner, 1988; Bikker et al., 1996; Noblet et al., 1994; Quiniou et al., 1999; Table 2.16). The energy content of empty BW gain over the 20–100 kg BW phase ranges from 10 MJ/kg in very lean animals to 20–22 MJ/kg in obese types of pigs (Noblet et al., 1994). Overall, this emphasizes the efforts for reducing the body fatness of growing pigs by either genetic selection or by nutritional manipulations.

Energy Requirements for Reproduction

Energy requirements of pregnant sows have been reviewed by Noblet et al. (1989, 1997). Energy requirements during pregnancy correspond to the sum of requirements for maintenance, uterine growth, and reconstitution of body reserves. Under specific conditions, additional requirements related to additional physical activity, or exposure to low temperatures, have to be taken into account. The basis for estimating energy requirements of pregnant sows is given in Table 2.15. The lower critical temperature of pregnant sows is 20°C to 22°C in single-housed females and is lower when straw bedding or group housing is used. In most practical situations, about two-thirds of the energy needed to meet the requirements of pregnant sows corresponds to the sows' maintenance requirement. The specific pregnancy requirement (i.e., uterine tissues gain) represents a negligible proportion of energy gain. However, in practice, it is higher if we consider the additional requirements for maintenance of the sow related to her additional metabolic BW because of uterine growth and the requirement for development of the mammary gland. The requirement for maternal tissues depends on the objective to realize a certain BW gain and its composition. This objective can be quite variable in multiparous sows according to their body condition at weaning.

Overall, energy requirements of pregnant sows can be variable according to the BW, the housing conditions, and the body condition at mating (Dourmad et al., 2008). Consequently, feeding pregnant sows the same quantities of feed as other pigs in a herd may result in large variations of performance, especially body condition at farrowing. Indeed, requirements for maintenance and uterine growth and possible requirements for thermoregulation and physical activity are priority. The energy deposited in maternal tissues will depend directly on the difference between feed allowance and these priority requirements. Energy deposition can be even lower because physical activity may be increased in sows with poor body condition or kept at low ambient temperatures (Noblet et al., 1997). Therefore, changes in behavior or physical activity can markedly affect the energy balance in pregnant sows. It is generally accepted that uterus growth follows an exponential curve (Noblet et al., 1985), which demonstrates low energy requirements for uterine tissues during the first two-thirds of pregnancy and more during the last third. According to the increase in BW during pregnancy, the requirements for maintenance will increase progressively. The consequence is that if daily feed supply is kept constant during pregnancy, the daily deposition of energy in maternal tissues will decrease progressively with the advancement of pregnancy and may even become negative during the last two to three weeks before farrowing (Dourmad et al., 1988; Young et al., 2004). This increased energy expenditure over the last third of pregnancy in sows indicates that an increase in energy supply during this period may be considered. The increased feed allowance at the end of pregnancy may also prepare the digestive tract for the rapid increase in feed intake after farrowing. These observations are illustrated in Table 2.17.

In lactating sows, the most important factor of variation is clearly the level of milk production of the sow. Milk production is difficult to measure in sows and it is usually estimated from litter growth (Noblet and Etienne, 1989; Table 2.15). Milk production depends on the genetic potential of the sow, litter size, and stage or duration of lactation (Etienne et al., 1998; Noblet et al., 1998).

Table 2.17 Effect of stage of pregnancy on energy utilization and activity in sows[1].

	Stage of gestation, weeks		
Item	5–6	9–10	14–15
Body weight, kg	182	207	224
Energy balance, MJ/d			
ME intake	28.6	28.4	28.8
Heat production	22.6	23.1	26.4
Retained energy			
Total	6.0	5.2	2.4
In uterus	0.4	1.3	2.6
In maternal tissues	5.7	4.2	−0.2
As protein	2.5	2.1	2.7
As fat	3.5	3.2	−0.3
Duration of standing, min	288	263	247
Activity heat production, MJ/d	5.7	6.2	6.9

[1] Adapted from Young et al. (2004), n = 12 sows.

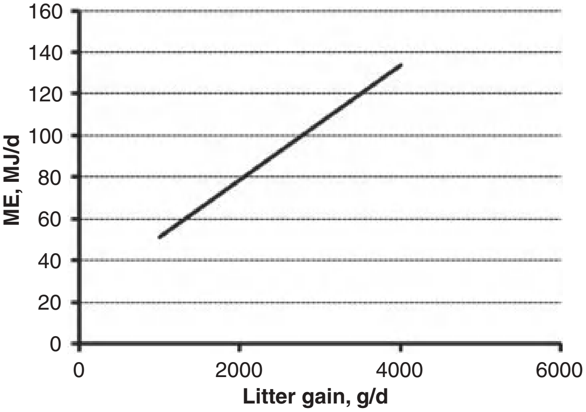

Figure 2.4 Effect of litter body-weight gain on energy requirements (MJ ME/d) of lactating sows. Calculations for a sow weighing 220 kg nursing 6 (1,000 g/d) to 13 (>3,000 g/d) piglets for 21 days.

The energy requirements during lactation correspond to the sum of maintenance requirements and energy requirements for milk production; the efficiency of ME for milk energy averages 72% (Table 2.15). The variation in energy requirements with litter gain is illustrated in Figure 2.4. At very high production levels (>3,000 g/day average litter BW gain), the feed requirement is greater than 8 kg per day. The calculation method also indicates that the additional ME requirement because of an additional litter BW gain is proportional to the litter weight gain difference. It averages 26 MJ ME per kg litter gain, or the equivalent of about 2 kg of a conventional feed per kg of additional kg litter BW gain. This approach is an easy and convenient technique to estimate the feed energy requirement in lactating sows, which is the equivalent of the sum of the requirement for maintenance (1.9–2.2 kg of feed per day for 200–250 kg sows) and the requirement for milk production (2 kg of feed per kg litter BW gain). Under most practical situations, lactating sows are unable to consume enough feed to meet their energy requirements, so they lose BW during lactation. The energy deficit and the subsequent BW loss are generally more important in primiparous sows. It is, therefore, critical to use all available techniques to maximize energy intake in lactating sows. This is beyond the scope of this chapter, but it is clear that ad libitum feeding is highly recommended. Energy intake can be increased by using energy-dense diets by reducing the DF content and increasing the fat content. Although sows that are fed these diets usually consume less feed, they will consume more energy. Nevertheless, a large fraction of the additional energy supply is excreted as fat in the milk with little direct benefit for the sow (Noblet et al., 1998).

Energy Requirements for Physical Activity

As mentioned previously, energy losses associated with physical activity cannot be accurately estimated. From a methodological point of view, the losses represent an uncontrolled source of variation of HP and may lead to inaccurate estimates of energy requirements, especially under conditions that markedly affect the behavior of the animals. Physical activity in swine represents a considerable proportion of energy expenditure, despite the low duration of standing in pigs and the reduced activity and locomotion when animals are kept indoors. This is due to four to five times

Table 2.18 Heat production related to physical activity in swine.

Item	Stage: Piglet	Growing pig			Pregnant sow
Housing:	Group	Group	Group	Single	Single
Feeding:	Ad libitum	Ad libitum	Ad libitum	Controlled	Restricted
Ambient temperature, °C	23	19–22	12	24	24
Body weight, kg	27	62	61	62	260
ME intake, MJ/d	21.7	31.1	33.5	29.2	35.6
Heat production, MJ/d	11.2	17.9	19.7	16.9	29.5
Activity heat production					
MJ/d	2.0	2.3	3.3	2.5	6.7
% heat production	17.9	12.8	16.9	14.7	22.6
% ME intake	9.2	7.4	10.0	8.5	18.7
Source[1]	1	2	2	3	4

[1] 1 = Collin et al. (2001a), 2 = Quiniou et al. (2001), 3 = Le Bellego et al. (2001a), and 4 = Ramonet et al. (2000).

greater energy expenditure per "unit" of physical activity in swine than in most other domestic species (Noblet et al., 1993). Results obtained in our group are summarized in Table 2.18. Even though a minimal level of physical activity is inevitable and is included in the estimate of ME_m, specific energy requirements for physical activity should be considered: for example, regarding stereotypic activities in pregnant sows or pigs kept outdoors. The most critical stage of pig production where physical activity is high and variable is the pregnancy period. Our studies indicate that the HP is increased by about 0.30 kJ/kg $BW^{0.75}$ per one additional minute in the standing position (Noblet et al., 1993; Ramonet et al., 2000; Le Goff et al., 2002; Young et al., 2004). For instance, in the study presented in table 2.17, the duration of standing ranged from 50 to 500 minutes per day among animals. The difference corresponds to a difference in feed requirement of approximately 700 g per day. More generally, activity represents a high (20% of ME intake) and variable (10–40% of ME intake) proportion of the energy expenditure in pregnant sows. This variability is the major source of variability in body condition of pregnant sows at farrowing. In growing pigs that are usually offered feed close to ad libitum intake, the activity HP is less variable and represents a lower fraction of ME intake (8–10%; Table 2.18).

Energy Requirements for Thermoregulation

When pigs are kept below their LCT, HP is increased to maintain body temperature. The concepts of thermoregulation and values of LCT in swine production have been reviewed by Noblet et al. (2001). However, the increased HP at temperatures below LCT is usually compensated for by higher feed intake, so that BW gain is maintained at low temperatures when pigs are offered feed ad libitum (Quiniou et al., 2001; see section on *Regulation of Energy Intake in Pigs*). The LCT is particularly high in newborn pigs (32°C–34°C) and during the first days after weaning (26°C–28°C) with a relative high susceptibility to cold stress during these periods (Noblet and Le Dividich, 1981; 1982). During other periods of swine production, LCT is lower (20°C–24°C) and requirements for thermoregulation depend on housing conditions (e.g., indoor versus outdoor, floor type, and group size) and feed intake. Additional feed requirements to maintain performance are illustrated in Figure 2.5 for growing–finishing pigs. Pregnant sows are frequently exposed to temperatures

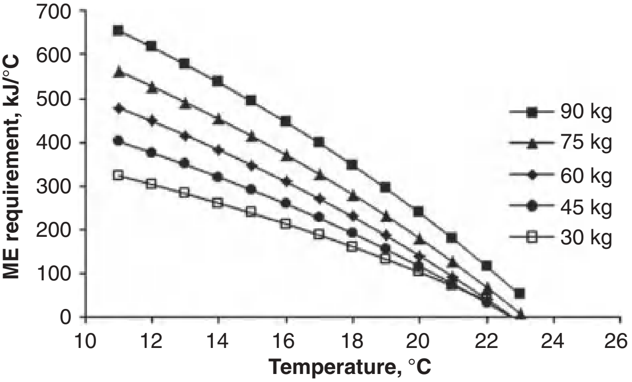

Figure 2.5 Energy requirement for thermoregulation in growing pigs according to their body weight (30–90 kg). (Adapted from Quiniou et al., 2001.)

below their LCT because of their relatively high LCT (>22°C) and simplified housing conditions. The HP can be increased by 10–20 kJ/kg $BW^{0.75}$ per 1°C decrease of ambient temperature below LCT (Geuyen et al., 1984) The higher rate is observed in individually housed sows and/or in poorly insulated thin sows (Noblet et al., 1997). In a 200-kg sow, the increase of HP due to cold stress should be compensated for by approximately 70 g of feed per 1°C. The LCT of lactating sows is low (<15°C) due to the high levels of feed intake and production, which are associated with a high rate of HP. In addition, heating is provided to the suckled piglets to improve comfort and survivability, so that cold is rarely a problem for lactating sows. More generally, the problem of cold stress has diminished in many countries due to improved insulation and quality of buildings. On the other hand, heat stress has become increasingly important in tropical or subtropical areas of the world, or during summer periods in temperate countries. The heat increment is not necessarily a loss of energy and can contribute to meeting the energy requirement for thermoregulation during cold periods (Table 2.10; Quiniou et al., 2001). Therefore, from a practical point of view, high heat-increment diets (i.e., high-fiber diets) are energetically more efficient under cold conditions than under thermoneutral or hot conditions (Noblet et al., 1985; 1989; 2001).

Response to Energy Intake

Growth of pigs depends on factors related to the animal itself (BW, sex, genotype, etc.), the supply of nutrients, and the climatic environment. Their response is also characterized by the partitioning of energy gain between protein and fat during the growing phase (Campbell and Taverner, 1988; Quiniou et al., 1999; van Milgen et al., 2008) or during pregnancy (Dourmad et al., 1996; 2008). The response during lactation is rather specific with a priority given to milk production at the expense of body reserves, and lactating sows are able to maintain milk production under conditions of a negative energy balance as long as their body reserves are not depleted too much (Noblet et al., 1998).

In the classical factorial view on energy utilization, energy will first be used to meet maintenance energy requirements, second for protein gain, and last for fat gain. However, this view of a succession of priorities is not necessarily appropriate because there is a relation between protein gain and lipid

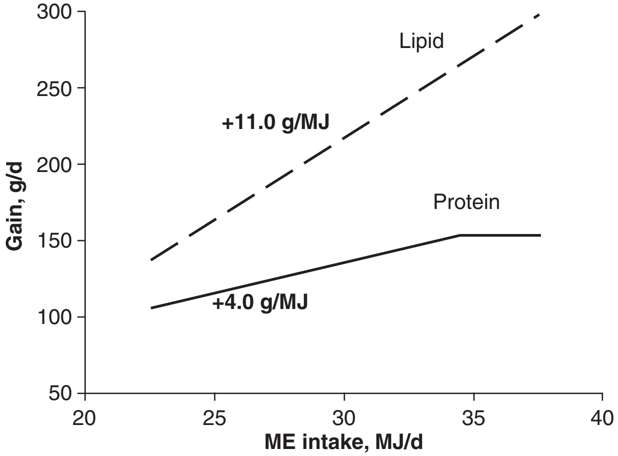

Figure 2.6 Response of protein and lipid gains to ME intake in 45- to 100-kg growing barrows (combined results of data obtained with two types of barrows). (Adapted from Quiniou et al., 1996.)

gain. When energy intake is restricted, both protein gain and lipid gain can be affected simultaneously and there seems to be an "obligatory" lipid gain. Most data demonstrate that the response of protein gain to energy intake can be described by a linear-plateau or curvilinear-plateau relationship, while the lipid gain response is practically close to linearity. The theoretically increased slope when the maximum protein deposition is reached is difficult to detect (Figure 2.6). As previously mentioned, the deposition rates of protein and lipid are associated with deposition rates of lean and adipose tissues and BW gain (Table 2.19). The important aspects of these relationships are (1) that the increase of gain (g per MJ ME) is much more pronounced for lipid or adipose tissue gain than for protein or lean tissue gains, so that adiposity of the body will increase with energy level (Table 2.20); (2) the slope for protein gain in the linear response phase is higher in leaner pigs or in boars (versus barrows) or in younger pigs (versus older pigs); and (3) with increasing energy intake, protein deposition will reach a plateau (PDmax) and energy given in excess of that required to reach

Table 2.19 Response of swine to energy intake.

	Growing pig		
Item	Male	Barrow	Pregnant sow
Body weight range, kg	45–100	45–100	205[1]
Variation, g/MJ of additional ME			
Protein	6.1	4.7	2.3
Fat	13.2	13.2	NA[2]
Lean	21.0	16.5	10.0
Adipose	9.7	9.7	12.0
Body weight gain	36.0	28.5	24.0
Source[3]	1	1	2

[1] Body weight at mating.

[2] NA = not available.

[3] 1 = Quiniou et al. (1996a,b; Large White × Piétrain crossbreds), and 2 = Dourmad et al. (1996).

the plateau will be used for fat gain. These aspects have been reviewed by Black et al. (1986), Quiniou et al. (1999), and van Milgen and Noblet (2003), and are partly illustrated in Table 2.19. Similar results are given in Table 2.19 for pregnant sows, for which the protein response is lower than in finishing pigs. The protein response (slope and PDmax) to energy intake is also affected by the ambient temperature. At high ambient temperatures, the slope for protein gain is reduced with a commensurate slight increase in the slope for fat gain (Le Bellego et al., 2002). Therefore, despite the lower feed intake at high ambient temperatures, which should favor a leaner carcass, the actual adiposity of the carcass is similar in ad libitum fed pigs raised at thermoneutrality or in hot conditions.

Feed Efficiency in Growing Pigs

From a technical point of view, an important criterion for evaluating the efficiency of pig production is the feed efficiency calculated as the quantity of feed or energy per kg of BW gain (or F:G). This F:G criterion can also be presented as:

$$\begin{aligned}
&\mathrm{F:G} = (\mathrm{ME\ intake}/[\mathrm{ME}])/(\mathrm{Energy\ gain}/[\mathrm{E}]_{\mathrm{ADG}})\ \mathrm{or} \\
&\mathrm{F:G} = (\mathrm{ME\ intake}/[\mathrm{ME}])/((\mathrm{ME\ intake} - \mathrm{MEm}) \times \mathrm{kg}/[\mathrm{E}]_{\mathrm{ADG}}))\ \mathrm{or} \qquad (2.21)\\
&\mathrm{F:G} = (1/[\mathrm{ME}]) \times (1/\mathrm{k_g}) \times [\mathrm{E}]_{\mathrm{ADG}} \times (\mathrm{FL}/[\mathrm{FL} - 1])
\end{aligned}$$

where [ME] is the ME concentration of the feed, $\mathbf{k_g}$ is the efficiency of ME for energy gain (see Table 2.8), $[\mathrm{E}]_{\mathbf{ADG}}$ is the energy concentration of BW gain, and FL is the feeding level as a multiple of MEm. This formula indicates that F : G is reduced when [ME] of the feed is increased and also when FL is increased with a lower relative contribution of energy intake used for maintenance. However, as indicated above, $[\mathrm{E}]_{\mathbf{ADG}}$ is increased at higher energy intakes with a subsequent increase of F:G. Therefore, these two effects of FL on $[\mathrm{E}]_{\mathbf{ADG}}$ and on FL/[FL − 1] are opposite and F:G remains relatively constant over a rather large range of FL (Table 2.20). However, at high feed intake, especially those above the ME intake required to attain PDmax (Figure 2.6), $[\mathrm{E}]_{\mathrm{ADG}}$ increases rapidly and the effect of FL/[FL − 1] becomes smaller, so that F:G increases (Table 2.20). On the other hand, at very low feed intake, the effect of FL/[FL-1] is important with a subsequent increased F:G value. Practically, this means that the ME intake required to minimize F:G is usually below ad

Table 2.20 Effect of energy supply on growth performance and body composition of growing pigs (45–100 kg BW)[1,2].

	Energy supply, MJ ME/d				
Item	22.6	26.7	29.4	32.2	37.6
BW gain, g/d	622	738	820	931	1,013
Feed cost, MJ ME/kg BW gain	36.4	36.2	35.8	34.6	37.1
Body protein content[3]	17.2	16.6	16.5	16.3	16.0
Body lean content[3]	56.1	54.2	53.6	53.7	52.6
Body lipid content[3]	18.6	21.0	22.0	22.4	22.8
Adipose tissues content[3]	12.0	14.2	15.1	15.2	15.7

[1] Adapted from Quiniou et al. (1996).

[2] BW = body weight.

[3] As a percentage of the empty BW (i.e., BW - gut fill) at slaughter, and empty BW is equivalent to 95% of live BW.

Table 2.21 Comparative growth performance of boars, barrows, and gilts[1,2].

Item	Boars	Gilts	Barrows
Feed intake, kg/d	2.41	2.45	2.70
BW gain, g/d	1,069	988	1,032
Feed cost, kg/kg BW gain	2.26	2.48	2.62

[1] Adapted from Quiniou et al. (2010), 63 to 152 days of age.
[2] BW = body weight.

libitum feed intake, especially in pigs with a lower potential for protein gain and/or a high appetite. As such, a slight energy restriction, especially during the finishing phase, may be recommended. This also means that, at a given FL value, the F:G is as low as the $[E]_{\mathbf{ADG}}$ is low in connection with a reduced fat content in BW gain. In conclusion, the best solution for improving F:G is to reduce the adiposity of the carcass by minimizing the fat-to-protein ratio in BW gain.

Depending on the ME content of the feed and the BW range, the F:G in 25- to 100-kg pigs ranges between 2.5 and 3.0 in most practical situations, with lower values for boars than for barrows, and intermediate values for females (Table 2.21). This also means that the BW gain achieved by 1 kg of feed ranges between 350 and 400 g, which is equivalent to 25–30 g BW gain per MJ ME of feed (Table 2.22). However, pigs are raised mainly for producing lean meat and it is important to maximize the quantity of lean gain or the energy gain in lean tissues per unit of feed. Indicative values are given in Table 2.22 for boars and barrows (15–17 g lean gain per MJ ME). Calculations given in Table 2.22 also indicate that about 40% and 13% of ME intake are retained in the BW gain or in the lean-tissue gain in growing pigs, respectively.

In most parts of the world, male pigs are (surgically) castrated to avoid boar taint problems in meat products. However, boars are raised in some areas (e.g., Australia and UK) where there is a tendency not to castrate the males for welfare considerations and for economical reasons. Boars can also be raised up to a few weeks before slaughter with a late immunocastration (Dunshea et al., 2001). The comparison of gilts, barrows, and boars, in terms of energy utilization, indicates that feed intake depends on gender (boar = gilt < barrow) with the lowest feed cost in boars (Table 2.21). In fact, castration reduces the potential of the pig for protein gain with a subsequent higher fat gain that is accentuated by the relative hyperphagy of barrows. The BW gain, lean gain, or energy gain

Table 2.22 Effect of castration on the efficiency of pig growth (40–100 kg BW)[1,2].

Item	Boars	Barrows[3]	
ME intake, MJ/d	35.1	37.1	(106)
BW gain, g/d	1,096	1,014	(92)
Protein gain, g/d	150	144	(96)
Lipid gain, g/d	232	255	(110)
BW gain, g/MJ ME	31.2	27.3	(87)
Lean gain, g/MJ ME	16.9	15.0	(89)
Body energy gain, MJ/MJ ME	0.39	0.40	(101)
Lean energy gain, MJ/MJ ME	0.14	0.13	(91)

[1] Adapted from Quiniou et al. (1995) and J. Noblet (unpublished data).
[2] BW = body weight.
[3] Parentheses = % of boars.

in lean tissues per unit of feed energy intake are higher for boars. However, the body energy gain per unit of energy intake is better in barrows due a greater fraction of energy gain that is retained as fat (Table 2.22). This example of the castration of males indicates that an improvement in feed efficiency (boars versus barrows) does not necessarily correspond to an improvement in overall energy efficiency. The same conclusion will hold for the impact of genetic improvement for leaner carcasses and/or faster growth.

Regulation of Energy Intake in Pigs

Under ad libitum conditions, it is important to evaluate the ability of the pig to consume enough feed or energy to meet the requirements or the objectives in terms of rate of growth, protein gain, and fat gain. It is not the purpose of this chapter to consider all aspects of feed intake regulation in swine. In this section, we want to briefly describe only some general aspects of energy intake in pigs in connection with major animal factors such as BW, physiological stage or gender, and major environmental factors such as feed energy concentration and ambient temperature.

Feeding patterns have been described in piglets, growing pigs, and lactating sows kept under conventional environmental conditions (Table 2.23). In brief, these studies indicate that the number of meals per day decreases when BW increases and the studies confirm that pigs, at any stage of production, are predominantly diurnal (with less than one-third of their activity occurring during the night). This diurnal behavior is even more pronounced in heavier pigs or in lactating sows with two main consumption peaks, one in the morning and one in the late afternoon (Figure 2.7). However, this diurnal behavior consumption can interact with climatic environment, such that under hot temperatures during the day and cooler temperatures at night, there may be an increased proportion of feed consumed during the nocturnal period. This is particularly noticeable in lactating sows (Quiniou et al., 2000; Renaudeau et al., 2003). Pregnant sows are often fed restrictively and consume their feed immediately after the distribution, unless it is a high-fiber feed in large volume, distributed only once a day.

In growing pigs, the voluntary feed intake increases curvilinearly with BW (NRC, 1998; Figure 2.8), but the rate of increase is affected by growth potential (e.g., genotype, sex) of the pig (Quiniou et al., 1999a). The rate of increase is also highly dependent on ambient temperature with

Table 2.23 Feeding behavior in swine.

	Stage:	Piglet	Growing pig				Lactating sow
	Breed:	Crossbred	Meishan	Piétrain	Crossbred		Crossbred
Item	Housing:	Group	Single	Single	Group	Group	Single
Body weight range, kg		20–30	20–60	20–60	30–90	30–90	270
Temperature, °C		23	24	24	19–22	29	22
Feed intake, g/d		1,502	1,659	1,622	2,395	1,820	6,600
Number of meals/d		14.4	14.4	7.3	11.2	10.1	7.4
Meal size, g		114	125	250	248	205	972
Diurnal feed intake, %		67	61	64	65	62	80
Source[1]		1	2	2	3	3	4

[1] 1 = Collin et al. (2001), 2 = Quiniou et al. (1999), 3 = Quiniou et al. (2000), and 4 = Quiniou et al. (2000).

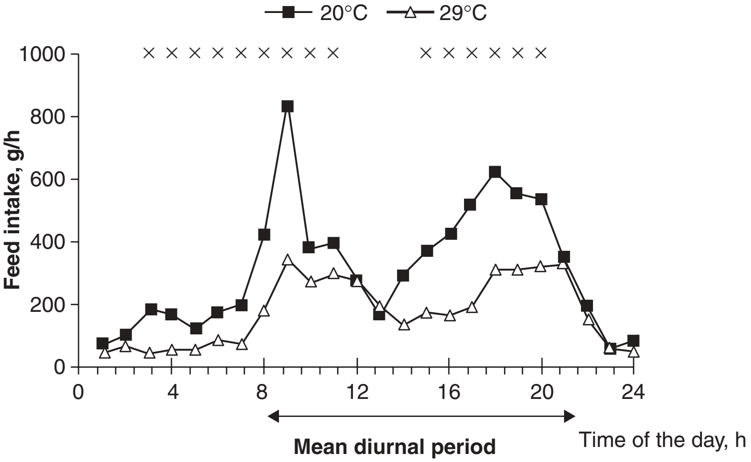

Figure 2.7 Effect of temperature on kinetics of daily feed intake in Large White lactating sows. (Adapted from Renaudeau et al., 2002.)

smaller rates of increase at high ambient temperatures, which means that heavier pigs are more sensitive to heat stress than lighter pigs (Nienaber et al., 1997; Figure 2.8). In lactating sows, voluntary feed intake is dependent on body size or parity number with lower intakes in primiparous sows (O'Grady et al., 1985; Dourmad et al., 1994; Neil et al., 1996). As growing pigs, lactating sows are particularly susceptible to heat stress by markedly reducing their voluntary feed intake at high ambient temperatures (Schoenherr et al., 1989). They are even more affected by ambient temperature changes according to their particularly high voluntary feed intake at thermoneutrality (Figure 2.9). In addition, the reduction in voluntary feed intake per 1°C change is as high as ambient temperature is high, with a reduction averaging 200 g/°C between 20°C and 25°C and up to 500 g/°C between 25°C and 30°C in lactating sows (Quiniou and Noblet, 1999); corresponding values would be 10 g/°C and 30 g/°C in 25-kg piglets (Collin et al., 2001) and 40 g/°C and 70 g/°C in 60-kg growing pigs (Quiniou et al., 2000). These negative effects of high temperatures on voluntary feed intake in

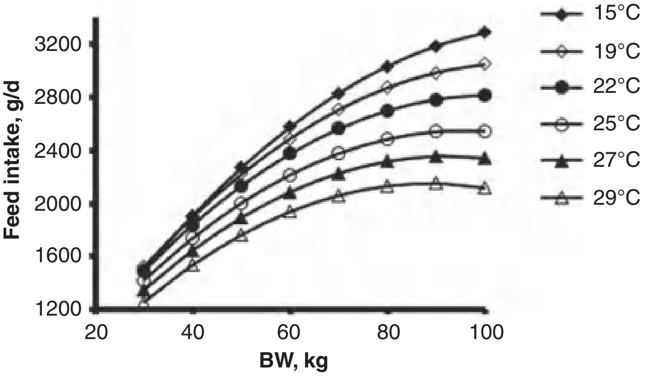

Figure 2.8 Effects of body weight (BW) and ambient temperature on voluntary feed intake in growing pigs. (Adapted from Quiniou et al., 2000a.)

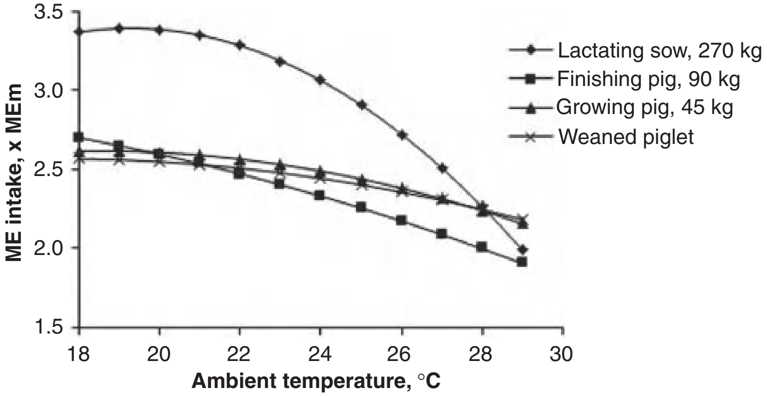

Figure 2.9 Effect of ambient temperature on feed intake in piglets (Collin et al., 2001), growing pigs (Quiniou et al., 2000), and lactating sows (Quiniou and Noblet, 1999). Feed intake is expressed as a multiple of the ME requirement for maintenance.

sows can even be worse under high relative humidities in tropical areas (Renaudeau et al., 2003). More generally, the exposure to high ambient temperatures is associated with a reduced ability of the growing pig or the lactating sow to dissipate their HP and a potential risk of hyperthermy. As a result, the best adaptation consists of reducing energy intake and the inevitable heat associated with the ingestion and the metabolic utilization of feed energy. The magnitude of these effects is the most pronounced for lactating sows.

Diet energy density can be modified by including fiber-rich ingredients that reduce the energy concentration or fat-rich ingredients that increase the energy concentration (Table 2.12). Because one limiting factor of pigs' growth in practical conditions is energy intake, a lot of attention has been focused on the relationship between feed intake, growth, feed efficiency, body composition, and energy concentration of the feed. A literature review revealed pertinent data: In each study, at least four energy densities were compared, and protein-to-energy ratios were as constant as possible. In most studies, pigs were kept individually and/or under favorable climatic conditions. An increase in energy concentration is usually associated with a reduction in voluntary feed intake, but the reduction is less important than the energy density, so that energy intake is almost systematically increased (Figure 2.10). However, in most studies, there is a plateau DE intake at the highest energy densities, or the increase becomes negligible when the lowest energy concentration is quite high. In agreement with this effect, BW gain is increased at higher energy concentrations with a plateau for BW gain at the highest energy densities. Such an effect of diet energy density on energy intake has also been demonstrated in lactating sows, but with a limited interest for the sow because most additional ingested energy as fat is exported in the milk (Noblet et al., 1998). Finally, this beneficial effect of high dietary energy densities on energy intake can be utilized in growing pigs or lactating sows exposed to heat stress. High-energy diets can attenuate the effect of high ambient temperature on pig performance (Le Bellego et al., 2002; Renaudeau et al., 2002).

Summary

Energy systems are based on the concept that an energy value can be attributed to a feed so that it can be compared with a requirement that is expressed on the same scale. In this chapter, we

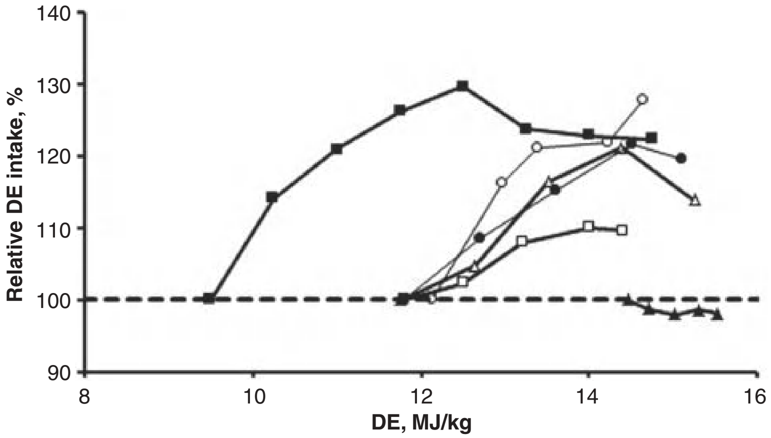

Figure 2.10 Effect of diet energy (DE) concentration on voluntary energy intake in growing pigs (as a percentage of the DE intake at the lowest DE content in each study). (Adapted from Chadd, 1999; Stein and Easter, 1996; Smith et al., 1999; Campbell and Taverner, 1986; and J. Noblet, unpublished data.)

confirmed that the situation is far more complex, with different energy values attributed to the same feed according to the type of pig receiving the diet and the implementation of a feed technology. Different energy systems have been proposed and based on the steps of energy utilization. The NE system is probably as far as we can go nowadays while maintaining the concepts of "value" and "requirement" in feed formulation. In reality, there are interactions among the energy supply, the environment, and the animal. The only way to deal with the complexity of these interactions is through modeling (Whittemore and Fawcett, 1976; Black et al., 1986; Birkett and de Lange, 2001; van Milgen et al., 2008). Although considerable progress has been made in this area, nutritional models of swine nutrition vary widely in scope. To be implemented on a large scale in the field, nutritional models should provide a compromise between "scientific truth" (or scientific perception) and robustness of the system. In that respect, it is probably too early to bury the classical concepts of energy nutrition outlined in this chapter.

References

Barea, R., S. Dubois, H. Gilbert, P. Sellier, J. van Milgen, and J. Noblet. 2010. Energy utilization in pigs selected for high and low residual feed intake. J. Anim. Sci. 88:2062–2072.

Brouwer, E. 1965. Report of subcommittee on constants and factors. Page 441 in Proc. 3rd Symp. Energy Metabolism. K. L. Blaxter, ed. Academic Press, London.

Bikker, P., M. W. A. Verstegen, and R. G. Campbell. 1996. Performance and body composition of finishing gilts (45–85 kg) as affected by energy intake and nutrition in earlier life. II. Protein and lipid accretion in body components. J. Anim. Sci. 74:817–826.

Birkett, S., and K. de Lange. 2001. Limitations of conventional models and a conceptual framework for a nutrient flow representative of energy utilization by animals. Br. J. Nutr. 86:647–659.

Black, J. L., R. G. Campbell, I. H. Williams, K. J. James, and G. T. Davies. 1986. Simulation of energy and amino acid utilization in the pig. Res. Dev. Agric. 3:121–145.

Boisen, S., and M. W. A. Verstegen. 1998. Evaluation of feedstuffs and pig diets. Energy or nutrient-based evaluation systems? II. Proposal for a new nutrient-based evaluation system. Acta Agric. Scandinavica, Sec. A Anim. Sci. 40:86–94.

Campbell, R. G., and M. R. Taverner. 1988. Genotype and sex effects on the relationship between energy intake and protein deposition in growing pigs. J. Anim. Sci. 66:676–686.

Chabeauti, E., J. Noblet, and B. Carré. 1991. Digestion of plant cell walls from four different sources in growing pigs. Anim. Feed Sci. Techn. 32:207–213.

Collin, A., J., van Milgen, and J. Le Dividich. 2001b. Modelling the effect of high, constant temperature on feed intake in young growing pigs. Anim Sci. 72:519–527.

CVB. 1994. Veevoedertabel. Centraal Veevoederbureau in Nederland, Lelystad, The Netherlands.

Cozannet, P., Y. Primot, C. Gady, J. P. Métayer, M. Lessire, F. Skiba, and J. Noblet. 2010. Energy value of wheat distillers grains with solubles for growing pigs and adult sows. J. Anim. Sci. 88:2382–2392.

de Lange, K., J. van Milgen, J. Noblet, S. Dubois, and S. Birkett. 2006. Previous feeding level influences plateau heat production following a 24 h fast in growing pigs. Br. J. Nutr. 95:1082–1087.

Dourmad, J. Y. 1991. Effect of feeding level in the gilt during pregnancy on voluntary feed intake during lactation and changes in body composition during gestation and lactation. Livest. Prod. Sci. 27:309–319.

Dourmad, J. Y., M. Etienne, A. Prunier, and J. Noblet. 1994. The effect of energy and protein intake of sows on their longevity. Livest. Prod. Sci. 40:87–97.

Dourmad, J. Y., M. Etienne, and J. Noblet. 1996. Reconstitution of body reserves in multiparous sows during pregnancy: Effect of energy intake during pregnancy and mobilization during the previous lactation. J. Anim. Sci. 74:2211–2219.

Dourmad, J. Y., J. Noblet, M. C. Père, and M. Etienne. 1998. Mating, pregnancy and pre-natal growth. Pages 129–153 in *A Quantitative Biology of the Pig*. I. Kyriazakis, ed. CAB International, Wallingford, UK.

Dourmad, J. Y., M. Etienne, A. Valancogne, S. Dubois, J. van Milgen, and J. Noblet. 2008. INRAPorc: A model and decision support tool for the nutrition of sows. Anim Feed Sci. Technol. 143:372–386.

Dunshea, F. R., C. Colantoni, K. Howard, I. McCauley, P. Jackson, K. A. Long, S. Lopaticki, E. A. Nugent, J. A. Simons, J. Walker, and D. P. Hennessy. 2001. Vaccination of boars with a GnRH vaccine (Improvac) eliminates boar taint and increases growth performance. J. Anim. Sci. 79:2524–2535.

Emmans, G. 1994. Effective energy: A concept of energy utilization applied across species. Br. J. Nutr. 71:801–821.

Etienne, M., J. Y. Dourmad, and J. Noblet. 1998. The influence of some sow and piglet characteristics and of environmental conditions on milk production. Pages 285–299 in *The Lactating Sow*. M. W. A. Verstegen, P. J. Moughan, and J. W. Schrama, eds. Wageningen Pers, Wageningen, The Netherlands.

Fernandez, J. A., H. Jorgensen, and A. Just. 1986. Comparative digestibility experiments with growing pigs and adult sows. Anim. Prod. 43:127–132.

Galloway, S. T., and R. C. Ewan. 1989. Energy evaluation of tallow and oat groats for young swine. J. Anim. Sci. 67:1744–1750.

Geuyen, T. P. A., J. M. F. Verhagen, and M. W. A. Verstegen. 1984. Effect of housing and temperature on metabolic rate of pregnant sows. Anim. Prod. 38:477–485.

Jorgensen, H., K. E. Bach Knudsen, and P. K. Theil. 2001. Effect of dietary fibre on energy metabolism of growing pigs and pregnant sows. Pages 105–108 in *Energy Metabolism in Animals*. A. Chwalibog and K. Jakobsen, eds. EAAP Publ. No. 103. Wageningen Pers, Wageningen, The Netherlands.

Just, A., H. Jorgensen, and J. A. Fernandez. 1983. Maintenance requirement and the net energy value of different diets for growth in pigs. Livest. Prod. Sci. 10:487–506.

Karege, C. 1991. Influence de l'âge et du sexe sur l'utilisation de l'énergie et la composition corporelle du porc en croissance. PhD. Diss. Université de Montpellier, France.

Koong, L. J., J. A. Nienaber, J. C. Pekas, and J. T. Yen. 1982. Effects of plane of nutrition on organ size and fasting heat production in pigs. J. Nutr. 112:1638–1642.

Labussière, E, G. Maxin, S. Dubois, J. van Milgen, G. Bertrand, and J. Noblet. 2009. Effects of feed intake on protein and fat deposition in milk fed veal calves. Animal 3:557–567.

Labussière, E., J. van Milgen, C. de Lange, and J. Noblet. 2011. Maintenance energy requirements of growing pigs and calves are influenced by feeding level. J. Nutr. 141:1855–1861.

Le Bellego, L., J. van Milgen, and J. Noblet. 2001. Energy utilization of low protein diets in growing pigs. J. Anim. Sci. 79:1259–1271.

Le Bellego, L., J. van Milgen, and J. Noblet. 2002. Effect of high temperature and low protein diets on performance of growing–finishing pigs. J. Anim. Sci. 80:691–701.

Le Bellego, L., J. van Milgen, J. Noblet. 2002. Effects of high temperature on protein and lipid deposition and energy utilization in growing pigs. Anim. Sci. 75:85–96.

Le Dividich, J., and J. Noblet. 1986. Effect of dietary energy level on the performance of individually housed early-weaned piglets in relation to environmental temperature. Livest. Prod. Sci. 14:255–263.

Le Goff, G., and J. Noblet. 2001. Comparative digestibility of dietary energy and nutrients in growing pigs and adult sows. J. Anim. Sci. 79:2418–2427.

Le Goff, G, L. Le Groumellec, J. van Milgen, and J. Noblet. 2002. Digestive and metabolic utilization of dietary energy in adult sows: influence of level and origin of dietary fibre. Br. J. Nutr. 87:325–335.

Lovatto, P., D. Sauvant, J. Noblet, S. Dubois, and J. van Milgen. 2006. Effects of feed restriction and subsequent re-feeding on energy utilization in growing pigs. J. Anim. Sci. 84:3329–3336.

Neil, M., B. Ogle, and K. Anner. 1996. A two diet system and ad libitum lactation feeding of the sow. 1. Sow performance. Anim. Sci. 62:337–347.

Nienaber, J. A., G. L. Hahn, T. P. McDonald, and R. L. Korthals. 1996. Feeding patterns and swine performance in hot environments. Trans. ASAE 39:195–202.

Noblet, J., and J. Le Dividich. 1981. Energy metabolism of the newborn pig during the first 24 hrs of life. Biol. Neonate 40:175–182.

Noblet, J., and J. Le Dividich. 1982. Effect of environmental temperature and feeding level on energy balance traits in early weaned piglets. Livest. Prod. Sci. 9:619–632.

Noblet, J., J. Le Dividich, and T. Bikawa. 1985a. Interaction between energy level in the diet and environmental temperature on the utilization of energy in growing pigs. J. Anim. Sci. 61:452–459.

Noblet, J., W.H. Close, R.P. Heavens, and D. Brown. 1985b. Studies on the energy metabolism of the pregnant sow. Uterus and mammary tissue development. Br. J. Nutr. 53:251–265.

Noblet, J., and M. Etienne. 1987a. Metabolic utilization of energy and maintenance requirements in lactating sows. J. Anim. Sci. 64:774–781.

Noblet, J., and M. Etienne. 1987b. Metabolic utilization of energy and maintenance requirements in pregnant sows. Livest. Prod. Sci. 16:243–257.

Noblet, J., Y. Henry, and S. Dubois. 1987. Effect of protein and lysine levels in the diet on body gain composition and energy utilization in growing pigs. J. Anim. Sci. 65:717–726.

Noblet, J., J.Y. Dourmad, J. Le Dividich, and S. Dubois. 1989. Effect of ambient temperature and addition of straw or alfafa in the diet on energy metabolism in pregnant sows. Livest. Prod. Sci. 21:309–324.

Noblet, J., and M. Etienne. 1989. Estimation of sow milk nutrient output. J. Anim. Sci. 67:3352–3359.

Noblet, J., J. Y. Dourmad, and M. Etienne. 1990. Energy utilization in pregnant and lactating sows: Modelling of energy requirements. J. Anim. Sci. 68:562–572.

Noblet, J., P. Herpin, and S. Dubois. 1992. Effect of recombinant porcine somatotropin on energy and protein utilization in growing pigs: Interaction with capacity for lean tissue growth. J. Anim. Sci. 70:2471–2484.

Noblet, J., and J. M. Perez. 1993. Prediction of digestibility of nutrients and energy values of pig diets from chemical analysis. J. Anim. Sci. 71:3389–3398.

Noblet, J., and X. S. Shi. 1993. Comparative digestibility of energy and nutrients in growing pigs fed ad libitum and adult sows fed at maintenance. Livest. Prod. Sci. 34:137–152.

Noblet, J., X. S. Shi, and S. Dubois. 1993a. Energy cost of standing activity in sows. Livest. Prod. Sci. 34:127–136.

Noblet, J., X. S. Shi, and S. Dubois. 1993c. Metabolic utilization of dietary energy and nutrients for maintenance energy requirements in pigs: Basis for a net energy system. Br. J. Nutr. 70:407–419.

Noblet, J., C. Karege, and S. Dubois. 1994a. Prise en compte de la variabilité de la composition corporelle pour la prévision du besoin énergétique et de l'efficacité alimentaire chez le porc en croissance. Journées Rech. Porcine en France 26:267–276.

Noblet, J., H. Fortune, X. S. Shi, and S. Dubois. 1994b. Prediction of net energy value of feeds for growing pigs. J. Anim. Sci. 72:344–354.

Noblet, J., X. S. Shi, and S. Dubois. 1994c. Effect of body weight on net energy value of feeds for growing pigs. J. Anim. Sci. 72:648–657.

Noblet, J., and K. E. Bach Knudsen. 1997a. Comparative digestibility of wheat, maize and sugar beet pulp non-starch polysaccharides in adult sows and growing pigs. Pages 571–574 in *Digestive Physiology in Pigs*. J. P. Laplace, C. Février, and A. Barbeau, eds. INRA, Paris.

Noblet, J., J. Y. Dourmad, M. Etienne, and J. Le Dividich. 1997b. Energy metabolism in pregnant sows and newborn pigs. J. Anim. Sci. 75:2708–2714.

Noblet, J., M. Etienne, and J. Y. Dourmad. 1998. Energetic efficiency of milk production. Pages 113–130 in *The Lactating Sow*. M. W. A. Verstegen, P. J. Moughan, and J. W. Schrama, eds. Wageningen Pers, Wageningen, The Netherlands.

Noblet, J., C. Karege, S. Dubois, and J. van Milgen. 1999. Metabolic utilization of energy and maintenance requirements in growing pigs: Effect of sex and genotype. J. Anim. Sci. 77:1208–1216.

Noblet, J., and G. Le Goff. 2001. Effect of dietary fibre on the energy value of feeds for pigs. Anim. Feed Sci. Technol. 90: 35–52.

Noblet, J., J. Le Dividich, and J. van Milgen. 2001. Thermal environment and swine nutrition. Pages 519–544 in *Swine Nutrition*. 2nd ed. A. J. Lewis and L. L. Southern, eds. CRC Press, Boca Raton, FL.

Noblet, J., L. Le Bellego, J. van Milgen, and S. Dubois. 2001. Effects of reduced dietary protein level and fat addition on heat production and nitrogen and energy balance in growing pigs. Anim. Res. 50:227–238.

Noblet, J., B. Sève, and C. Jondreville. 2004. Nutritional values for pigs. Pages 25–35 in *Tables of Composition and Nutritional Value of Feed Materials: Pigs, Poultry, Cattle, Sheep, Goats, Rabbits, Horses, Fish*. D. Sauvant, J. M. Perez, and G. Tran, eds. Wageningen Academic Publishers, Wageningen and INRA ed., Versailles, The Netherlands.

Noblet, J., and J. van Milgen. 2004. Energy value of pig feeds: Effect of pig body weight and energy evaluation system. J. Anim. Sci. 82(E. Suppl.):E229–E238.

Noblet, J. 2006. Recent advances in energy evaluation of feeds for pigs. Pages 1–26 in *Recent Advances in Animal Nutrition 2005*. P. C. Garnsworthy, and J. Wiseman, eds. Nottingham Univ. Press, Nottingham, UK.

Noblet, J. 2007. Recent developments in energy and amino acid nutrition of pigs. Pages 21–48 in *Gaining the Edge in Pork and Poultry Production: Enhancing Efficiency, Quality and Safety*. J. A. Taylor-Pickard and P. Spring, eds. Wageningen Academic Publishers, Wageningen, The Netherlands.

Noblet, J., and Y. Jaguelin-Peyraud. 2007. Prediction of digestibility of organic matter and energy in the growing pig from an in vitro method. Anim. Feed Sci. Technol. 134:211–222.

NRC. 1998. *Nutrient Requirements of Swine*. 10th rev. ed. Natl. Acad. Press, Washington, DC.

O'Grady, J. F., P. B. Lynch, and P. A. Kearney. 1985. Voluntary feed intake by lactating sows. Livest. Prod. Sci. 12:355–365.

Quiniou, N., J. Noblet, J. van Milgen, and J. Y. Dourmad. 1995. Effect of energy intake on performance, nutrient and tissue gain and protein and energy utilisation in growing boars. Anim. Sci. 61:133–143.

Quiniou, N., J. Y. Dourmad, and J. Noblet. 1996a. Effect of energy intake on the performance of different types of pig from 45 to 100 kg body weight. 1. Protein and lipid deposition. Anim. Sci. 63:277–288.

Quiniou, N., J. Y. Dourmad, and J. Noblet. 1996b. Effect of energy intake on the performance of different types of pig from 45 to 100 kg body weight. 2. Tissue gain. Anim. Sci. 63:289–296.

Quiniou, N., and J. Noblet. 1999. Influence of high ambient temperatures on performance of multiparous lactating sows. J. Anim. Sci. 77:2124–2134.

Quiniou, N., S. Dubois, Y. Le Cozler, J. F. Bernier, and J. Noblet. 1999a. Effect of growth potential (body weight and breed/castration combination) on the feeding behaviour of individually-kept growing pigs. Livest. Prod. Sci. 61:13–22.

Quiniou, N., J. Noblet, J. Y. Dourmad, and J. van Milgen. 1999b. Influence of energy supply on growth characteristics in pigs and consequences for growth modelling. Livest. Prod. Sci. 60:317–328.

Quiniou, N., J. Noblet, and S. Dubois. 2000a. Voluntary feed intake and feeding behaviour of group-housed growing pigs are affected by ambient temperature and body weight. Livest. Prod. Sci. 63:245–253.

Quiniou, N., D. Renaudeau, S. Dubois, and J. Noblet. 2000b. Influence of high ambient temperatures on food intake and feeding behaviour of multiparous lactating sows. Anim. Sci. 70:471–479.

Quiniou, N., J. Noblet, J. van Milgen, and S. Dubois. 2001. Modelling heat production and energy balance in group-housed growing pigs exposed to cold or hot ambient temperatures. Br. J. Nutr. 85:97–106.

Quiniou, N., V. Courboulay, Y. Salaün, and P. Chevillon. 2010. Conséquences de la non castration des porcs mâles sur les performances de croissance et le comportement: comparaison avec les mâles castrés et les femelles. Journées Recherche Porcine 42:113–118.

Ramonet, Y., J. van Milgen, J. Y. Dourmad, S. Dubois, M. C. Meunier-Salaün, and J. Noblet. 2000. The effect of dietary fibre on energy utilisation and partitioning of heat production over pregnancy in sows. Br. J. Nutr. 84:85–94.

Renaudeau, D., N. Quiniou, and J. Noblet. 2001. Effect of high ambient temperature and dietary protein level on performance of multiparous lactating sows. J. Anim. Sci. 79:1240–1249.

Renaudeau, D., and J. Noblet. 2001. Effect of exposure to high ambient temperature and dietary protein level on sows milk production and performance of piglets. J. Anim. Sci. 79:1540–1548.

Renaudeau, D., J. L. Weisbecker, J. Noblet. 2003. Effects of season and dietary fibre on feeding behaviour of lactating sows in a tropical climate. Anim. Sci. 77:429–437.

Renaudeau, D., B. Bocage, and J. Noblet. 2006. Influence of energy intake on protein and lipid deposition in Creole and Large White growing pigs. Anim. Sci. 82:937–945.

Sauvant, D, J. M. Perez, and G. Tran. 2004. *Tables of Composition and Nutritional Value of Feed Materials: Pigs, Poultry, Cattle, Sheep, Goats, Rabbits, Horses, Fish*. Wageningen Academic Publishers, Wageningen, The Netherlands.

Schoenherr, W. D., T. S. Stahly, and G. L Cromwell. 1989. The effects of dietary fat or fiber addition on yield and composition of milk from sows housed in warm or hot environment. J. Anim. Sci. 67:482–495.

Schiemann, R., K. Nehring, L. Hoffmann, W. Jentsch, and A. Chudy. 1972. *Energetische Futterbevertung und Energienormen*. VEB Deutscher Landwirtschatsverlag, Berlin, Germany.

Skiba, F., J. Noblet, P. Callu, J. Evrard, and J. P. Melcion. 2002. Influence du type de broyage et de la granulation sur la valeur énergétique de la graine de colza chez le porc en croissance. Journées Rech. Porcine en France 34:67–74.

van Milgen, J., J. Noblet, S. Dubois, and J. F. Bernier. 1997. Dynamic aspects of oxygen consumption and carbon dioxide production in swine. Br. J. Nutr. 78:397–410.

van Milgen, J., J. F. Bernier, Y. Le Cozler, S. Dubois, and J. Noblet. 1998b. Major determinants of fasting heat production and energetic cost of activity in growing pigs of different body weight and breed/castration combination. Br. J. Nutr. 79:509–517.

van Milgen, J., and J. Noblet. 2000. Modelling energy expenditure in pigs. Pages 103–114 in *Modelling Nutrient Utilization in Farm Animals*. J. P. McNamara, J. France, and D.E. Beever, eds. CAB International, Oxon, UK.

van Milgen, J., J. Noblet, and S. Dubois. 2001. Energetic efficiency of starch, protein, and lipid utilization in growing pigs. J. Nutr. 131:1309–1318.

van Milgen, J., and J. Noblet. 2003. Partitioning of energy intake to heat, protein and fat in growing pigs. J. Anim. Sci. 81(E. Suppl. 2):E86–E93.

van Milgen, J., A. Valancogne, S. Dubois, J. Y. Dourmad, B. Sève, and J. Noblet. 2008. InraPorc: A model and decision support tool for the nutrition of growing pigs. Anim Feed Sci. Technol. 143:387–405.

Whittemore, C. T., and R. H. Fawcett. 1976. Theoretical aspects of a flexible model to simulate protein and lipid growth in pigs. Anim. Prod. 22:87–96.