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RECENT ADVANCES IN ENERGY EVALUATION OF FEEDS FOR PIGS

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Introduction

Feed is the most important cost of pig meat production (approximately 0.60) and the energy component represents the greatest proportion. Therefore, it is important to estimate precisely the energy value of feeds, either for best-cost formulation purposes or for adapting feed supply to energy requirements of animals. Evaluation of the energy content of pig feeds is, firstly and most commonly, based on their digestible (DE) or metabolizable (ME) energy. However, the closest estimate of the "true" energy value of a feed should be its net energy (NE) content which takes into account differences in metabolic utilization of ME between dietary components. In addition, NE is the only system in which energy requirements and diet energy values are expressed on a same basis which should theoretically be independent of feed characteristics. At each step of energy utilization (DE, ME or NE), different prediction methods can be used. An energy system corresponds then to the combination of one step of energy utilization and one prediction method. The objectives of this chapter paper are 1) to consider the main factors of variation of digestive and metabolic utilization of energy in pig feeds, 2) to present the available energy systems for pig feeds with emphasis given to NE systems, 3) to compare the energy systems and 4) to evaluate their ability for predicting pigs performance. Methodological aspects of energy evaluation of pig feeds and complementary information have been considered in previous reviews (Noblet and Henry, 1993; Noblet, 1996; Noblet, 2000; Noblet and van Milgen, 2004).

Energy utilization

DIGESTIVE UTILIZATION

For most pig diets, the digestibility coefficient of energy (DCe or DE:gross energy ratio) varies between 0.70 and 0.90 but the variation is larger for individual feed ingredients (0.10 to 1.00; Sauvant, Perez and Tran, 2004a,b). Most of the variation of DCe is related to the presence of dietary fiber (DF) which is less digestible than other nutrients (<0.50 vs 0.80-1.00 for starch, sugars, fat or protein; Table 1.1) and reduces the apparent fecal digestibility of other dietary components such as crude protein and fat (Noblet and Perez, 1993; Le Goff and Noblet, 2001). Consequently, DCe is linearly and negatively related to the DF content of the feed (Table 1.2). The coefficients relating DCe to NDF are such that NDF or DF essentially dilute the diet, at least in growing pigs. In other terms, even though DF is partly digested by the young growing pig, it provides very little DE to the animal (Noblet and van Milgen, 2004). The digestive utilization of DF varies with its botanical origin (Chabeauti, Noblet and Carré, 1991; Table 1.1) with subsequent variable effects of DF on dietary energy digestibility (Noblet, 2000). The DCe prediction equations presented in Table 1.2 represent therefore average equations for mixed feeds. They should not be applied to raw materials where specific relationships are to be used (Noblet and Henry, 1993; Noblet and Le Goff, 2001; Noblet, Bontems and Tran, 2003a).

Table 1.1. Digestibility of fibre fractions and energy in high fibre ingredients in growing pigs (G) and adult sows (S)[a].

	Wheat bran		*Corn bran*		*Sugar beet pulp*	
	G	*S*	*G*	*S*	*G*	*S*
Digestibility coefficient of						
Non-starch polysaccharides	0.46	0.54	0.38	0.82	0.89	0.92
Non cellulose polysaccharides	0.54	0.61	0.38	0.82	0.89	0.92
Cellulose	0.25	0.32	0.38	0.82	0.87	0.91
Dietary fiber[a]	0.38	0.46	0.32	0.74	0.82	0.86
Energy	0.55	0.62	0.53	0.77	0.70	0.76

[a] Adapted from Noblet and Bach-Knudsen (1997); dietary fibre = Non-starch polysaccharides + lignin

Table 1.2. Effect of diet composition (g/kg dry matter) on energy digestibility (DCe, %), ME:DE coefficient (%) and efficiency of utilization of ME for NE of mixed diets for growth (k_g, %) or maintenance (k_m, %)[a]

	Equation	*RSD*[b]	*Source*[c]
1	DCe = 98.3 - 0.090 x NDF	2.0	1
2	DCe = 96.7 - 0.064 x NDF	2.2	1
3	ME/DE = 100.3 - 0.021 x CP	0.5	1
4	k_g = 74.7 + 0.036 x EE + 0.009 x ST - 0.023 x CP - 0.026 x ADF	1.2	2
5	k_m = 67.2 + 0.066 x EE + 0.016 x ST	1.9	3

[a] CF: Crude Fibre, CP: crude protein, NDF: Neutral Detergent Fibre, EE: ether extract, ST: starch, ADF: Acid Detergent Fibre.
[b] Residual standard deviation
[c] 1: Le Goff and Noblet (2001) (n=77 diets ; equations 1 and 3 in 60 kg growing pigs and equation 2 in adult sows, respectively) ; 2 : Noblet *et al.* (1994a) (n=61 diets ; 45 kg pigs); 3: Noblet *et al.* (1993b) (n=14 diets; maintenance fed adult sows).

Digestibility of energy can be modified by technological treatments. Pelletting, for instance, increases the energy digestibility of feeds by about 1% (Skiba, Noblet, Callu, Evrard and Melcion, 2002). 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 1.3, the improvement in energy digestibility was mainly due to an improved digestibility of fat provided by maize or full-fat rapeseed. Consequently, the energy values of these ingredients depend greatly on the technological treatment. In the specific situation of a high-oil maize (75g oil/kg), 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 were 10.0 and 23.5 MJ DE/kg DM as mash and after pelleting, respectively (Skiba *et al.*, 2002).

Energy digestibility is affected by other factors than those related to the diet itself. In growing pigs, DCe increases with increasing body weight (BW; Noblet, Shi, Karege and Dubois, 1993a; Noblet and Shi, 1994; Noblet *et al.*, 2003a; Table 1.4). The largest effect of BW is observed when adult sows fed at pregnancy levels and (close to) ad libitum growing pigs are compared (Noblet and Shi, 1993; Le Goff and Noblet, 2001). In addition, the difference due to BW increase is most pronounced for high fibre diets or ingredients (Equations 1 and 2 in Table 1.2). Therefore, the negative effect of dietary fibre on DCe becomes smaller for heavier pigs or adult sows and the contribution of DF to energy supply becomes largely positive in heavier pigs. From a large data set of measurements (77 diets), Le Goff and Noblet

Table 1.3. Effect of pelletting and particle size on digestibility coefficient of fat and energy in growing pigs.

	Mash	*Pellet*
Corn-soybean meal diets[a]		
Fat	0.610	0.770
Energy	0.884	0.903
Wheat-soybean meal-full fat rapeseed diets[b]		
Fat	0.270	0.840
Energy	0.731	0.874
Wheat-corn-barley-soybean meal diets		
Energy[d]	0.758	0.773

[a] Mean of three diets containing 810 g maize and 155g soybean meal /kg (Noblet and Champion, 2003).
[b] One diet containing 600g wheat, 150g soybean meal and 200 g full fat rapeseed /kg; rapeseed was coarsely ground (Skiba *et al.*, 2002).
[d] Mean of 4 diets also containing variable amounts of fibre-rich ingredients (wheat bran, sugar beet pulp) (unpublished data)

Table 1.4. Effect on pig body weight on energy digestibility[a].

Stage	*BW, kg*	*DM intake, g/d*	*Coefficient of energy digestibility*
1	38	1250	0.826
2	49	1680	0.830
3	61	1940	0.836
4	72	2015	0.842
5	80	2060	0.848
6	90	2120	0.853
Total growth	35-95	1845	0.836

[a] Mean values obtained on 4 diets based on wheat and soybean meal and variable proportions of wheat bran, rapeseed oil and animal fat; measurements were carried out continuously on the same pigs from 35 to 95 kg; the effect of stage (or BW) on energy digestibility was significant ($P<0.01$); the interaction between pig stage and diet composition (i.e., fibre level) was also significant ($P<0.01$) (J. Noblet, unpublished data).

(2001) calculated that one g of NDF provided 3.4 and 6.8 kJ in 60 kg-growing pigs and mature sows, respectively. From the same data, it was also shown that the DE difference between adult sows and growing pigs is proportional to the amount of indigestible organic matter as measured in the growing pig (4.2 kJ/g on average; Noblet, Sève and Jondreville, 2004a,b; 2003a; Noblet and Tran, 2004a,b; Figure 1.1).

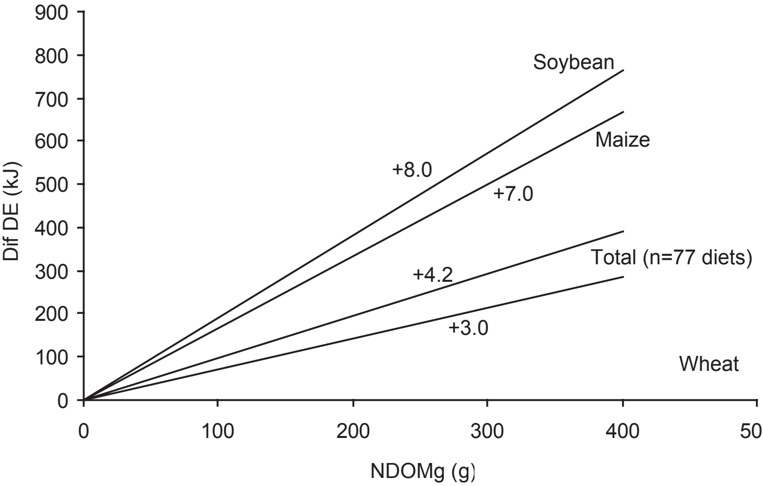

Figure 1.1 Relationship between difference between DE value in adult sows and DE value in growing pigs (dif DE) and indigestible organic matter in growing pigs (NDOM) for some families of ingredients (adapted from Noblet *et al.*, 2003a)

This improvement in energy digestibility with increasing BW is due to the greater digestibility of the DF fraction (Table 1.1) related to a greater hindgut digestive capacity in heavier pigs and, more importantly, a slower rate of passage in the digestive tract (Le Goff, van Milgen and Noblet, 2002a). The attenuated negative effects of DF on protein and fat digestibility (i.e., reduced endogenous losses) also contribute to the reduced effect of DF on DCe in adult pigs. In the adult sow, this improved digestibility of energy is little due to the effect of reduced feeding level, at least at feeding levels used during the pregnancy period (Table 1.5). On the other hand, a high feeding level (*ad libitum*) may deteriorate slightly the energy digestibility in growing pigs (Table 1.5). In the lactating sow fed high levels (6 to 9 kg/day), the energy digestibility is also higher than in the growing pig (Table 1.6), so that the difference between the adult sow and the growing pig would be rather independent of the physiological status and/or the feeding level of the adult sow. This means that values obtained in adult dry sows at pregnancy feeding levels should be used for both pregnant and lactating sows, these values being higher than the values for growing pigs (Table 1.7).

The DCe or the DE differences between sows and growing pigs, for a given level of dietary fibre, also depend on the origin of DF or on the physico-

Table 1.5. **Effect of feeding level on digestive utilization of energy in growing pigs and adult dry sows.**

Stage	*Growing pig*[a]		*Adult sow*[b]		
Feeding level	1	2	1	2	3
Body weight, kg	40.1	43.3	260	260	260
Feed intake, g DM/d	1106	1478	2090	2536	2966
Coefficient of energy digestibility	0.832	0.826	0.852	0.856	0.859

[a] Mean of 2 compound feeds containing 130 and 210g NDF/kg; the effect of feeding level was more pronounced in the high NDF feed ($P < 0.05$) (J. Noblet, unpublished data)

[b] Mean of 4 compound feeds based on maize, wheat, barley, peas, soybean meal and variable proportions of wheat bran, soybean hulls, sugar beet pulp, wheat straw and rapeseed oil (J. Noblet, unpublished data)

Table 1.6. Effects of body weight and physiological stage on energy digestibility in pigs.

	Trial 1[a]		*Trial 2*[b]	
	Growing pig	*Dry sow*	*Growing pig*	*Lactating sow*
Body weight, kg	60	227	62	246
Feed intake, g DM/day	2044	2119	2062	4850
Coefficient of energy digestibility	0.772[a]	0.805[b]	0.799[a]	0.849[b]

[a] Mean of 3 compound feeds based on maize, wheat, barley, peas, soybean meal and variable proportions of wheat bran, sunflower meal, maize gluten feed and animal fat (J. Noblet, unpublished data)

[b] Mean of 3 compound feeds based on maize, wheat, barley, peas, soybean meal and variable proportions of wheat bran, sunflower meal, maize gluten feed and animal fat (Etienne, Noblet, Dourmad and Castaing, 1997)

Table 1.7. Digestible energy value of some ingredients for growing pigs and adult sows[a].

	DE, MJ/kg[b]		
Ingredient	*Growing pig*	*Adult pig*	*a*[c]
Wheat	13.85	14.10	3.0
Barley	12.85	13.18	2.5
Maize	14.18	14.77	7.0
Peas	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
Maize gluten feed	10.80	12.59	7.0
Soybean hulls	8.37	11.46	8.0

[a] Adapted from Sauvant *et al.* (2004a, b)

[b] As fed.

[c] kJ difference in DE between adult sows and growing pigs per g of indigestible organic matter in the growing pig (Noblet *et al.*, 2003a; 2004b).

chemical properties of DF. This is illustrated in Table 1.1 where the effects of DF from wheat bran, maize bran and sugar beet pulp are compared or in Figure 1.2 for wheat and maize products. Detailed information on the effect of origin of DF on DCe in both growing pigs and adult sows has been given by Noblet and Le Goff (2001). These results indicate that growing pigs have a limited ability to digest DF with small differences between fibre 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 1.7 also illustrate the effect of botanical origin with smaller differences between physiological stages for Graminae (wheat, barley, wheat bran), Brassicaceae (rapeseed) or Compositae (sunflower) and more pronounced differences for Leguminosae (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 (Table 1.7; Figure 1.1; Noblet and Tran, 2004b).

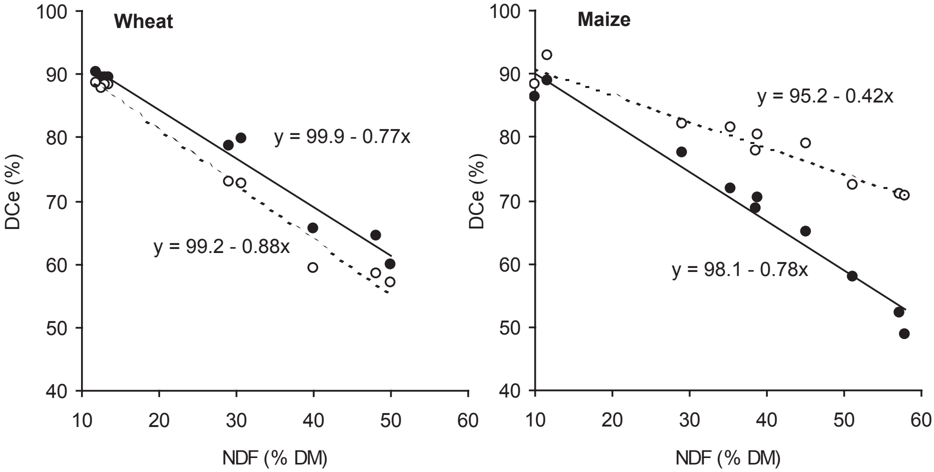

Figure 1.2 Effect of NDF content on energy digestibility (dE, %) of wheat and maize and their by products in growing pigs (opened symbols) and adult sows (closed symbols) (adapted from Noblet and Le Goff, 2000)

Little information concerning comparative digestibility in piglets and growing pigs is available. Considering that piglets are usually fed low-fiber diets for which the effect of BW is minimized, piglets can, from a practical point of view, be considered as growing pigs concerning the digestive utilization of energy. For growing pigs, especially when they are raised up to heavy BW (i.e. late finishing pigs), energy values adapted to each stage of growth should theoeretically be used. 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, whatever their BW. This means that, in practice, only two different DE values should be given to feeds: one for piglets and growing pigs and one for adult sows (Table 1.7; Sauvant *et al.*, 2004a, b). This proposal is the most justified for fibrous ingredients. A second consequence of the changes of DCe with BW (Table 1.4) is that digestibility trials should be carried out at approximately 60 kg BW (Noblet, 1996; Noblet *et al.*, 2003a) in order to be representative of the total weaning-growing-finishing period.

ME:DE RATIO

The ME content of a feed is the difference between DE and energy losses in urine and gases (i.e., as methane and hydrogen). In growing pigs, average energy loss in methane is equivalent to 0.4% of DE intake (Noblet, Fortune, Shi and Dubois, 1994a). In sows fed at maintenance level, methane production represents a much greater proportion of DE intake (0.015; Noblet and Shi, 1993) and may reach up to 0.03 of DE intake in sows fed very high fibre diets (Ramonet, van Milgen, Dourmad, Dubois, Meunier-Salaun and Noblet, 2000; Le Goff, Le Groumellec, van Milgen and Noblet, 2002b). More generally, methane production increases with BW and DF level in the diet (Noblet and Shi, 1993; Bakker, 1996; Jorgensen, Bach-Knudsen and Theil, 2001). From the compilation of literature data conducted by Le Goff *et al.* (2002a) and unpublished data, Noblet *et al.* (2004a,b) proposed that methane energy is equivalent to 0.7 and 1.3 kJ per g of fermented DF in growing pigs and adult sows, respectively. Unlike humans, hydrogen production in pigs is rather low and can be ignored.

Energy loss in urine represents a variable proportion of DE since urinary energy depends greatly on the urinary nitrogen excretion. At a given stage of production, urinary nitrogen excretion is mainly related to the (digestible) protein content of the diet. Consequently, the ME:DE ratio is linearly related to the dietary protein content (Table 1.2). In most situations, the ME:DE ratio of complete feeds is approximately 0.96. However, this mean value cannot be applied to single feed ingredients (Noblet, Fortune, Dupire and Dubois, 1993c). Consequently, equation 3 in Table 1.2 cannot be applied beyond the range of typical CP contents of pig diets (120 to 200g/kg) and is therefore not directly applicable to most ingredients. The most appropriate solution is then to estimate urinary energy (kJ/kg DM intake) from urinary nitrogen (g/kg DM intake). The following equations have been proposed:

Urinary energy (kJ/kgDM intake) in growing pigs = 192 + 31 x Urinary nitrogen (g/kg DM intake)

Urinary energy (kJ/kg DM intake) in sows = 217 + 31 x Urinary nitrogen (g/kg DM intake)

For implementing these equations to feed ingredients, it can be assumed that urinary nitrogen represents usually 0.50 of digestible nitrogen (or 0.40 of total dietary nitrogen) at most physiological stages of pig production (Noblet *et al.*, 2003a, 2004a,b).

Metabolic utilization of ME

Net energy is defined as ME minus heat increment associated with metabolic utilization of ME and to the energy cost of ingestion, digestion and some physical activity. It is generally calculated as the sum of (estimated or measured) fasting heat production and retained energy (Noblet and Henry, 1993; Noblet *et al.*, 1994a). The NE content, as a percentage of ME content (k) corresponds to the efficiency of utilization of ME for NE. Apart from variations due to the final utilization of ME (e.g., maintenance, protein gain *vs* fat gain *vs* milk production), k varies according to the chemical characteristics of the feed since nutrients are not used with the same efficiencies (Noblet, Shi and Dubois, 1993b, Noblet et al., 1994a; Noblet, Shi and Dubois, 1994b; Table 1.2). The variations in k are due to differences in efficiencies of ME utilization between nutrients with the highest values for fat (~90%) and starch (~82%) and the lowest (~60%) for DF and crude protein. These values were confirmed in recent trials (van Milgen, Noblet and Dubois, 2001). The differences in efficiencies between nutrients also mean that heat increment (per unit of energy) associated with metabolic utilization of energy is higher for crude protein and DF than for starch or ether extract (Noblet *et al.*, 1994a; Table 1.8). Finally, NE measurements conducted in pigs which differ for their BW and the composition of BW gain suggest that the efficiency of ME for NE is little affected by the composition of BW gain, at least under most practical conditions (Noblet *et al.*, 1994b). Similarly, the ranking between nutrients for efficiencies is similar in adult sows fed at maintenance level and in lean fast growing pigs (Noblet, Shi, Fortune, Dubois, Lechevestrier, Corniaux, Sauvant and Henry, 1994c).

The comparison of our results on ME utilization with literature data and the practical consequences on energy evaluation system have been reviewed by Noblet (1996; 2000) and Noblet and van Milgen (2004). They have also been validated in recent experiments conducted in our laboratory (Ramonet *et al.*, 2000; Le Bellego, van Milgen and Noblet, 2001; Noblet, Le Bellego, van Milgen and Dubois, 2001; van Milgen *et al.* 2001; Le Goff, Dubois, van Milgen and Noblet, 2002c; Figure 1.3). They confirm that the increase of dietary crude protein results in an increased HP (Table 1.9).

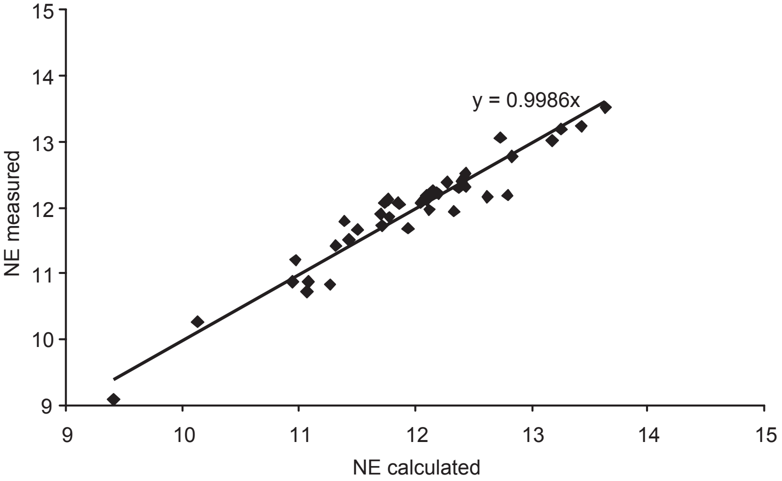

Figure 1.3 Relationship between measured NE values of compound feeds (n=41; indirect calorimetry method) and NE calculated according to NE prediction equations (mean of equations NEg4 and NEg7 in Table 1.11). Adapted from Le Bellego *et al.* (2001), Le Goff *et al.* (2002c), Noblet *et al.* (2001), Noblet *et al.* (2003), van Milgen *et al.* (2001) and Noblet *et al.*, unpublished data.

Table 1.8. Energy value of starch, crude protein and fat according to energy systems[a].

	Starch	*Crude protein[b]*	*Crude fat[b]*
Energy values, kJ/g[b]			
Digestible energy	17.5 (1.00)	20.6 (1.18)	35.3 (2.02)
Metabolizable energy	17.5 (1.00)	18.0 (1.03)	35.3 (2.02)
Net energy	14.4 (1.00)	10.2 (0.71)	31.5 (2.19)
Heat production, kJ/g	3.1	7.8	3.8
Heat production, proportion of NE	0.22	0.76	0.12

[a] Adapted from Noblet *et al.* (1994a) (n = 61 diets)

[b] In brackets, energy values as proportion of starch; crude protein and crude fat are assumed to be 0.90 digestible; starch is 1.00 digestible.

Table 1.9. Energy utilization of low protein diets.

	Trial 1[a]		*Trial 2*[b]	
Crude protein, g/kg	*174*	*139*	*219-174*	*172-127*
Digestible lysine, g/MJ NE	*0.76*	*0.76*	*1.05-0.72*	*1.05-0.72*
Energy balance, MJ/kg BW$^{0.60}$				
ME intake	2.46	2.46	2.57	2.57
Heat production	1.42[x]	1.37[y]	1.40[x]	1.34[y]
Energy retained	1.05[x]	1.09[y]	1.17[x]	1.23[y]
ME/DE	0.955[x]	0.967[y]	0.957[x]	0.967[y]
NE/ME	0.732[x]	0.753[y]	0.739[x]	0.759[y]

[a] From Le Bellego *et al.* (2001) and Noblet *et al.* (2001); 65-kg pigs; wheat, maize and soybean meal based diets; the low protein diet was supplemented with HCl-lysine, methionine, threonine, tryptophan, isoleucine and valine.

[b] From Noblet, van Milgen, Carré, Dimon, Dubois, Rademacher and van Cauwenberghe (2003); in 25, 55 and 85 kg pigs; wheat, corn and soybean meal based diets. Values for CP and lysine levels are given for the 25 and 85 kg pigs; values at 55 kg were intermediary.

[x,y] Values are significantly different (P<0.05) if different exponents are indicated (within trial).

On the other hand, inclusion of fat contributes to reduction of HP. Diets with low crude protein and/or high fat contents can then be considered as low heat increment diets and are potentially better tolerated under conditions of heat stress (Renaudeau, Quiniou and Noblet, 2001; Le Bellego, van Milgen and Noblet, 2002). The effect of DF on HP remains unclear (Noblet and Le Goff, 2001). In some trials, HP is significantly increased when DF is increased (Noblet, Dourmad, Le Dividich and Dubois, 1989; Noblet *et al.*, 1993b; 1994a; Ramonet *et al.*, 2000; Solund Olesen, Jorgensen and Danielsen, 2001; Rijnen, Verstegen, Heetkamp and Schrama, 2003) while, in other trials, HP remains constant or even decreases (Rijnen, Verstegen, Heetkamp, Haaksma and Schrama, 2001; Le Goff *et al.*, 2002b, c). From a biochemical perspective, HP should increase and most results are consistent with this. However, addition of DF may change the behavior of animals (i.e., reduced physical activity) or the overall metabolism, thereby decreasing HP (Schrama, Bosch, Verstegen, Vorselaars, Haaksma and Heetkamp, 1998). Furthermore, the effects of DF probably also depend on the nature of DF, and the specific effect of sugarbeet pulp DF (Rijnen *et al.*, 2001) cannot be generalized to other DF sources. Differences in the design of trials and limits of methodologies may also explain these discrepancies. Finally, another interesting aspect illustrated in the results of van Milgen *et al.* (2001) concerns the HP associated to the utilization of dietary protein either for protein deposition or for lipid deposition (and ATP production). 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.

Energy systems

DIGESTIBLE AND METABOLIZABLE ENERGY

Apart from direct measurement on pigs, the DE and ME values of raw materials can be obtained from feeding tables (NRC, 1998; Sauvant *et al.*, 2004a,b). But the utilization of these tabulated values should be restricted to ingredients having chemical characteristics similar or close to those in the tables. As illustrated in the previous section, DCe is affected by BW of the animals. It is therefore appropriate to use DE and ME values adapted to each BW class. However, from a practical point of view, it is suggested to use only two values, one for "60 kg" pigs which can be applied to piglets and growing-finishing pigs and one for adult pigs applicable to both pregnant and lactating sows. Values given in most feeding tables are typically obtained in the 40- to 60-kg pig. The INRA & AFZ feeding tables (Sauvant *et al.*, 2004a,b) provide DE and ME values for these two stages and an illustration is given in Table 1.7.

The DE content of compound feeds can be obtained by adding the DE contributions of ingredients and assuming no interaction, which is usually the case (Noblet and Shi, 1994; Noblet *et al.*, 2003a; Table 1.10).

Table 1.10. Additivity principle for formulating pig diets: validation for combination of high fibre ingredients and fat sources[a].

Ingredients	*BW, kg*	*Energy digestibility* *Measured*	 *Calculated*	*Reference*
Rapeseed oil (80g/kg) + dietary fibre sources[b] (250 g/kg)	45, 100 & 150	0.65	0.66	1
Animal fat (30g/kg) + rapeseed oil (30g/kg) + wheat bran (300 g/kg)	35 to 95 kg	0.69	0.68	2
Soybean oil (60g/kg) + wheat bran	65	0.65	0.65	2
(300g/kg) or maize bran (300g/kg)	245	0.76	0.75	2

[a] Calculated energy digestibility corresponds to the value obtained from the combination of energy digestibilities obtained on ingredients when measured alone; measured digestibility is the measured energy digestibility on the mixture

[b] Mixture of wheat bran (250g/kg), soybean hulls (250g/kg), sugar beet pulp (250g/kg) and wheat straw (250g/kg)

[c] References: 1: Noblet and Shi (1994); 2: unpublished data.

When the actual composition of the feed is unknown, the possibility is to use prediction equations based on chemical criteria (Noblet and Perez, 1993; Le Goff and Noblet, 2001) or estimates from near infrared or in vitro methods (Boisen and Fernandez, 1997; Jaguelin-Peyraud and Noblet, 2003). Such equations cannot be used for feed ingredients.

NET ENERGY

All published NE systems for pigs combine the utilization of ME for maintenance and for growth (Just, 1982; Noblet *et al.*, 1994a and 1994b) or for fattening (Schiemann, Nehring, Hoffman, Jentsch and Chudy, 1972). The system used in the Netherlands (CVB, 1994) and the subsequent adjustments are based on the equations proposed by Schiemann *et al.* (1972). The “system” used by NRC (1998) for estimating NE values combines results from direct measurements using a questionable animal model (piglet) and estimates from prediction equations. The available NE systems have been described by Noblet (1996; 2000). More recently, Boisen and Verstegen (1998) proposed new concepts for estimating the NE value of pig feeds (so-called physiological energy) and based on the combination of *in vitro* digestion methods for estimating digestible dietary components and biochemical coefficients for evaluating the ATP potential production from the components. Complementary and theoretical knowledge concerning endogenous secretions could also be included in this approach. Apart from difficulties for implementing the *in vitro* digestion methods, this approach assumes that energy is used exclusively for ATP production – which is not the case in growing pigs, for instance.

The system proposed by Noblet *et al.* (1994a) and applied in the INRA & AFZ feeding tables (Sauvant *et al.*, 2004a,b) is based on a large set of measurements (61 diets). These results have been validated in recent trials (Le Bellego *et al.*, 2001; Noblet *et al.*, 2001; van Milgen *et al.*, 2001; Le Goff *et al.*, 2002c; Figure 1.3) and its applicability for predicting performance of animals has been demonstrated (see last section). The equations that have been generated from these measurements for predicting NE are given in Table 1.11. They are all based on information available in conventional feeding tables and are applicable to single ingredients and compound feeds (Noblet *et al.*, 1993c) and at any stage of pig production (Noblet *et al.*, 1994c). They can therefore determine a correct hierarchy between feeds for both growing pigs and pregnant or lactating sows. However, 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 then necessary for prediction of NE content of pig feeds. In fact, this information represents the most limiting factor for predicting energy values of pig feeds.

Table 1.11. Equations for prediction of net energy in feeds for growing pigs (NEg; MJ/kg dry matter; composition as g per kg of dry matter).

Equation[a]	*RSD, %*	*Source*[b]
NEg2a = 0.0113 x DCP + 0.0350 x DEE + 0.0144 x ST + 0.0000 x DCF + 0.0121 x DRes	2.0	1
NEg2b = 0.0121 x DCP + 0.0350 x DEE + 0.0143 x ST + 0.0119 x SU + 0.0086 x DRes	2.4	2
NEg4 = 0.703 x DE - 0.0041 x CP + 0.0066 x EE - 0.0041 x CF + 0.0020 x ST	1.7	1
NEg7 = 0.730 x ME - 0.0028 x CP + 0.0055 x EE - 0.0041 x CF + 0.0015 x ST	1.6	1

[a] CF: Crude Fibre, CP: crude protein, EE: ether extract, ST: starch, DCP: digestible CP, DEE: digestible EE, DCF: digestible CF, DRes: digestible residue (i.e., difference between digestible organic matter and other digestible nutrients considered in the equation). The NEg suffix corresponds to the equation number, as given by Noblet *et al.* (1994a).

[b] 1: Noblet *et al.* (1994a); 2: Noblet *et al.* (2004).

INRA-AFZ FEEDING TABLES

The INRA-AFZ feeding tables (Sauvant *et al.*, 2004a,b) provide DE, ME and NE values of feeds for pigs as well as digestibility coefficients of major dietary components and organic matter. A lot of effort was put into the estimation of reliable NE values, as it is now agreed that NE content is the best assessment of the “true” energy value for pigs. Two companion articles to the INRA-AFZ tables were produced later on (Noblet *et al.*, 2003a; Noblet and Tran, 2004a). An Excel spreadsheet has also been produced in order to make available all the equations that were used in the preparation of energy values that are presented in the feeding tables. It must be stressed that the energy values for energy and digestibility coefficients have been obtained only from literature values, thus excluding a “copy/paste” of previous feeding tables. The concepts used originate from studies conducted at INRA over the last 20 years.

Estimation of the energy value of feed ingredients for pigs requires several steps. The first one is the estimation of gross energy (GE); equations are proposed in the tables and in the Excel spreadsheet. In a second step, digestible energy (DE) is calculated as GE multiplied by the apparent faecal digestibility coefficient for energy (DCe). The energy losses in urine are calculated using the amount of nitrogen excreted in the urine and the losses in the form of gas from degraded cell walls. The metabolizable energy content (ME) is the difference between the DE value and the energy losses in urine and gas. The net energy (NE) value is estimated using the equations proposed by Noblet *et al.* (1994a; Table 1.11) that can be applied to both the growing pig and the adult sow (Noblet *et al.* 1994c). Details on the methods and the calculations for getting the values reported in the tables are given by Noblet *et al.* (2003a; 2004a,b) and Noblet and Tran (2004a,b).

Ingredients presented in the feeding tables have a fixed composition and a corresponding energy value. However, the ingredients composition can be variable in practice, especially for by-products with expected variations in energy values. The basic approach used for calculating the energy values reported in the tables cannot be used routinely for energy evaluation of such feed materials; simplified methods have then been proposed (Noblet *et al.*, 2003a; Noblet and Tran, 2004a,b). In brief, for prediction of DE in growing pigs (DEg), prediction equations of GE and DCe have been produced per family of ingredients (Noblet *et al.*, 2003a, Excel spreadsheet: Noblet and Tran, 2004a,b) and they can be applied for adjusting the DE value according to chemical composition; usually, a dietary fibre criteria is used for that correction. For estimating DE in adult pigs (DEs) from DE in growing pigs (DEg), the DEs/DEg ratio cannot be considered as constant when the chemical composition of an ingredient differs from the one in the tables. The following formula:

$$\text{DEs} / \text{DEg}, \% = 100 + (a / 100) \times (100 - \text{Ash}) \times (100 - b \times \text{DCe}) / \text{DEg}$$

has been proposed in which “a” represents the amount of additional DE in adult pigs per g of undigestible organic matter in growing pigs (Table 1.7) and “b” the ratio between organic matter digestibility and energy digestibility. Ash content is in % of dry matter and DCe in %; DEg is expressed in MJ/kg of dry matter. Values of “a” and “b” are listed in the spreadsheet and by Noblet *et al.* (2003a).

The ME/DE ratio of a feed material, for an average catabolism rate of proteins, is assumed to be constant when its chemical composition (nitrogen content) changes within reasonable limits. Values for ME/DE of feed materials are listed in the Excel spreadsheet (Noblet and Tran, 2004b) or can be obtained from the INRA-AFZ tables per family of ingredients. Like the ME/DE ratio, the NE/ME ratio for a given ingredient does not vary much with the chemical composition. The NE can then be calculated as ME x (NE/ME). Values for NE/ME ratio are listed in the spreadsheet (Noblet and Tran, 2004b).

ENERGY REQUIREMENTS

Energy requirements are expressed on different bases. In *ad libitum* fed pigs, they consist mainly in fixing the diet energy density according to regulation of feed intake (appetite) or growth potential of the pig, to climatic factors or to economical conditions. In restrictively fed growing pigs or in reproductive sows, it is necessary to define feeding scales according to expected performance (dose response approach). Finally, in more sophisticated or more theoretical approaches (factorial approach or modelling approach), it is necessary to determine the components of energy requirements (maintenance, growth, milk production, thermoregulation, etc). Whatever the level of approach, most trials and recommendations were conducted according to DE and ME estimates for feeds and conclusions were expressed as DE or ME values. In addition, the recommendations were obtained with rather conventional feeds, i.e. cereals-soybean meal based diets whose efficiency of ME utilization in growing pigs is close to 0.74 according to the prediction equations proposed in Table 1.11. This latter value also corresponds to the average efficiency obtained for 61 diets by Noblet *et al.* (1994a). The proposal is then to estimate the NE recommendations (diet energy concentration, daily energy requirements, components of energy requirements, etc.) as DE or ME requirements multiplied by 0.71 or 0.74, respectively. For factorial approaches, NE for maintenance can be estimated as 750 kJ/kg $BW^{0.60}$ in growing pigs (Noblet *et al.*, 1994a; Le Bellego *et al.*, 2001) and 320 kJ/kg $BW^{0.75}$ in reproductive sows (Noblet *et al.*, 1993b; Noblet, Dourmad, Etienne and Le Dividich, 1997), respectively. The NE requirement for growth or milk production is equal to the amount of retained or exported energy.

In the case of adult sows fed slightly above their maintenance energy levels (i.e., pregnancy level), it has been demonstrated that the measured NE value is slightly higher but proportional to the NE value calculated according to the equations of Table 1.11 (obtained in growing pigs) and DE, ME or digestible nutrients measured in adult sows (Noblet *et al.*, 1993b and 1994c). As presented earlier in this review, it is then suggested to calculate the NE value for adult sows from the equations obtained in growing pigs (Table 1.11) but with DE, ME or digestible nutrients obtained in adult sows. This approach has been used in the INRA&AFZ feeding tables (Sauvant *et al.*, 2004a,b). Similar to growing pigs (previous paragraph), it is then also suggested to transform the DE or ME recommendations for adult sows to NE recommendations by multiplying them by 0.71 or 0.74, respectively. Very little information is available on ME utilization in lactating sows (Noblet *et al.*, 1997) and, to our knowledge, the effect of diet characteristics on k in lactating sows has not been quantified. The proposals for estimating the NE requirements of empty or pregnant sows can then be extrapolated to lactating sows.

Comparison of energy systems

DE, ME AND NE SYSTEMS

From the equations reported in Tables 1.2 and 1.11, it is obvious that the hierarchy between feeds obtained in the DE or ME systems will vary in the NE system according to the specific chemical composition. Since NE represents the best compromise between the feed energy value and energy requirement 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 system (Noblet *et al.*, 1993a). These conclusions are more clearly demonstrated in Table 1.8 for pure dietary componens and in Table 1.12 for a series of ingredients: high fat (animal or vegetable fat, oil seeds) or high starch (tapioca, cereals) ingredients are penalized in the DE system while protein rich and/or fibre rich (meals, fibrous by-products) ingredients are favored. For mixed ingredients, the negative effect of protein or fiber (i.e., protein sources) on efficiency of DE or ME for NE is partly counterbalanced by the positive effect of starch or fat (i.e., energy sources).

Table 1.12. **Relative digestible, metabolizable and net energy values of ingredients for growing pigs[a].**

	DE	*ME*	*NE*	*NE/ME*
Animal fat	2.43	2.52	3.00	0.90
Tapioca	1.01	1.03	1.10	0.81
Maize	1.03	1.05	1.12	0.80
Rapeseed (full-fat)	1.60	1.62	1.68	0.78
Wheat	1.01	1.02	1.06	0.78
Barley	0.94	0.94	0.96	0.77
Diet	1.00	1.00	1.00	0.75
Pea	1.01	1.00	0.98	0.73
Soybean (full-fat)	1.16	1.13	1.08	0.72
Wheat bran	0.68	0.67	0.63	0.71
Soybean meal	1.07	1.02	0.82	0.60
Rapeseed meal	0.84	0.80	0.64	0.60
Amino acids mixture	1.48	1.42	1.46	0.78

[a] From Sauvant *et al.* (2004a,b). Within each system, values are expressed as percentages of the energy value of a diet containing 674g wheat, 160g soybean meal, 25g fat, 50g wheat bran, 50g peas, 40g minerals and vitamins and 1.0 g HCl-lysine / kg; the so-called amino acids mixture contains 500g HCl-lysine, 250g threonine and 250g methionine/kg.

NET ENERGY SYSTEMS

As explained above, several equations (and therefore systems) for prediction of NE of feeds are available (Schiemann *et al.*, 1972: NEs; Just, 1982: NEj; Noblet *et al.*, 1994a: NEg; CVB, 1994: NEnl). The proposal of NRC (1998) cannot really be considered as a system. These systems were established according to different hypotheses and under different experimental conditions. Therefore, different NE systems do not provide interchangeable estimates (Noblet, 1996) and the NE value depends on the choice of the system. For comparing these NE systems, the measured NEg values of 61 diets (Noblet *et al.*, 1994a) have been compared to their calculated NEs, NEj and NEnl values. Comparison with the system proposed by Boisen and Verstegen (1998) was not possible at this stage. If NEg is considered on a basis of 100, average NEs, NEj and NEnl are equivalent to about 94, 83 and 96. As explained by Noblet (1996; 2000), these average differences are mainly due to differences in estimates of the fasting heat production. However, this ratio also depends on diet composition. It is slightly decreased for NEs and NEnl when dietary starch content is increased, which means that starch sources are underestimated according to these systems. However, both NEg and NEnl provide relatively consistent energy values and, in the near future, a new NEnl system based on the INRA equations is expected to be proposed. With regard to NEj, the NEj/NEg ratio is decreased when starch and fat levels are increased and increased for higher levels of crude protein or dietary fibre. It can then be considered that the NEj system is close to a ME system. For this reason, it is progressively abandoned in Denmark. Finally, recent trials in which NE value of pig diets has been measured in growing pigs or in adult sows confirm the accuracy of the NEg system since measured NE values and predicted values according to equations presented in Table 1.11 were very similar (Figure 1.3).

As previously mentioned, it is extremely important to use the same energy system for expressing the diet energy values and the animal energy requirements. As illustrated above and in the next section, the NE/DE or NE/ME ratios differ according to the chemical characteristics of the feed which means that for providing a given quantity of NE, different DE or ME supplies are necessary according to the chemical characteristics of the feed. It is then obvious that the only energy system in which the requirements are independent on the diet characteristics is the NE system. In addition, a NE system is supposed to describe more accurately the “true” energy value of a feed. Consequently, it is highly recommended to use one NE system for both pig requirements and energy values. Furthermore, in order to be totally consistent, NE values from different systems cannot be combined.

ENERGY SYSTEMS AND PERFORMANCE

In diet formulation, chemical and ingredient composition of diets for growing-finishing pigs and reproductive sows is manipulated in order to achieve 1) a minimum level of recommended dietary energy and 2) minimum ratios between lysine and energy, and 3) minimum ratios between essential amino acids and lysine (i.e., ideal protein). These criteria are more relevant to the characteristics of the animal (i.e., BW, genotype, physiological stage) or, in other terms, the nutritional requirements. The expression of nutritional values of feeds should be as consistent as possible with the expression of nutrient requirements. From that point of view, the most consistent expression of energy value and energy requirements is theoretically based on NE. In addition, apart from minimizing the cost of diets, an objective such as minimizing heat dissipation (in heat stressed animals, for instance) can be met when formulating on a NE basis. More generally, the quality of a nutritional evaluation system is given by its ability to predict the performance of the animals independently of the diet composition (or specific effects of dietary components).

The data presented in Tables 1.13 and 1.14 illustrate the relationship between energy system and performance and confirm that NE as calculated according to Noblet *et al.* (1994a; 2004a,b) is a better predictor of performance than DE or ME. In other words, the NE value is a satisfactory estimate of the energy value of feeds. On the other hand, DE or ME systems overestimate the energy value of high CP diets and underestimate the energy value of fat rich diets.

Table 1.13. Energy requirements of ad libitum fed growing-finishing pigs according to energy evaluation system)[a].

	Diet 1	*Diet 2*
Diet composition, g/kg		
Crude protein	188	145
Starch	459	509
Fat	2.5	26
Energy intakes, MJ/d		
DE	38.9[a]	37.3[b]
ME	37.1[a]	36.1[b]
NE	27.6	27.5
Nitrogen excretion, g/kg BW gain	50.2[a]	30.9[b]

[a]Performance were measured between 30 and 100 kg at a temperature of 22°C; energy intakes are adjusted by covariance analysis for similar BW gain (1080 g/day) and carcass composition at slaughter; diets had the same ratio between digestible lysine and NE (0.85 and 0.70 g/MJ in the growing and finishing periods, respectively) and the ratios between essential amino acids and lysine were above recommended values; diet composition values represent the mean of the growing diet and the finishing diet. Adapted from Le Bellego *et al.* (2002).

Table 1.14. Performance of ad libitum fed growing-finishing pigs according to dietary fat supplementation: comparison of energy systems[a].

	Performance	*Relative performance*			
Fat supplementation, g/kg	*0*	*0*	*20*	*40*	*60*
Feed intake, g/d	2200	1.00	0.973	0.977	0.941
ME intake, MJ/d	29.7	1.00	1.000	1.033	1.021
NE intake, MJ/d	22.5	1.00	1.006	1.043	1.036
BW gain, g/d	737	1.00	1.005	1.057	1.061
Feed to BW gain:					
kg/kg	2.98	1.00	0.966	0.923	0.889
MJ ME/kg	40.2	1.00	0.996	0.978	0.965
MJ NE/kg	30.4	1.00	1.001	0.988	0.979

[a] Between 36 and 120 kg BW; in three successive periods; at each period, the protein:energy ratio (Digestible lysine to NE) was the same for all diets; the protein:energy ratio decreased over successive periods. Protein and energy values of diets (corn/soybean meal/choice white grease) were calculated according to Sauvant *et al.* (2004a,b). Adapted from de la Llata, Dritz, Tokach, Goodband, Nelssen and Loughin (2001).

In the specific case of low protein diets which are more and more recommended in order to reduce the impact of pig production on the environment (Le Bellego *et al.*, 2002; Table 1.13), it is clear that their energy value is underestimated when formulated on DE or ME bases. This may explain the tendency of fatter carcasses when low protein diets are formulated on a DE basis: animals are in fact getting more energy than expected from DE supply. This also illustrates the importance of formulation criteria for interpreting performance results and the risks of manipulating the composition of diets according to inaccurate or inappropriate nutritional criteria. The use of ileal digestible (or available) amino acids and NE are then highly recommended.

Conclusions

In this chapter, it has been demonstrated that energy value of pig feeds can be measured according to different criteria (DE, ME or NE) and different systems for each criterion. The most advanced and practically applicable energy evaluation system appears the NE system proposed by Noblet *et al.* (1994a) for which energy values of most ingredients used in pig diets are available (Sauvant *et al.*, 2004a,b); complementary methods have been proposed for evaluating any ingredient that differs in terms of chemical composition from those defined in feeding tables. In addition, these authors have proposed energy values that are different for growing and adult pigs. Technological treatment can also affect the energy value. Unfortunately, current information is insufficient to take this systematically into consideration; it should be an area for future research. This chapter also indicates that the relative energy density or the hierarchy between ingredients depends on the energy system (DE vs ME vs NE) with considerable variation between ingredients or compound feeds when either fat or crude protein contents deviate from values in standard diets.

Significant improvements in prediction of energy value of pig feeds will come from an improved knowledge of energy and nutrient digestibility, which depends on chemical characteristics of the feed, (bio)technological treatments, animal factors (body weight) and interactions between these factors. Since DF is the main factor of variation of digestive utilization of the diet, more emphasis should be given to routine techniques that identify the nutritional and physiological "quality" and the role of DF. Improving feed evaluation systems will eventually consist in using more mechanistic approaches based on nutrient supplies (i.e., glucose, amino acids, etc.) which are used for meeting requirements for ATP, protein synthesis, and fat synthesis by the animal. Modeling approaches are then essential for describing both digestion of nutrients and metabolic utilization of nutrients. Energy value (expressed as a caloric value) will then become an auxiliary variable of the model.

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